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REPORT ON THE MECHANICAL AND THERMAL PROPERTIES OF TUNGSTEN AND TZM SHEET PRODUCED IN THE REFRACTORY METAL SHEET ROLLING PROGRAM

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PART I

TO

BUREAU OF NAVAL WEAPONS CONTRACT NO. N600(19)-59530

SOUTHERN RESEARCH INSTITUTE
2000 9th Avenue S. Birmingham, Alabama 35205

REPORT ON

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Part 1

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Bureau of Naval Weapons
Contract No. N600(19)-59530

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35205
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ABSTRACT

This report describes an evaluation program that was performed to obtain preliminary design data for tungsten and TZM sheet produced in the Refractory Metal Sheet Rolling Program. Tungsten sheet 0.060- and 0.10-in. thick, and TZM sheet 0.020-, 0.040-, and 0.060-in. thick, were investigated. Both materials were studied in the optimum (warm worked and stress relieved) and recrystallized conditions. Mechanical properties evaluated included tensile, notched-tensile, compression, bearing, shear, creep, thermal-stability, weld joint efficiency. The recrystallization and bend-transition temperatures were also determined. Physical properties that were evaluated included density, thermal expansion, thermal conductivity and specific heat. Tensile and bend evaluations were performed on the TZM sheet after application of two commercial coatings, PFR-6 and W-3.

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REPORT ON

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Part 1

INTRODUCTION

The increasing need for materials capable of withstanding high operating temperatures in advanced aircraft and space vehicles has created increasing consideration of refractory metals and their alloys for engineering applications. In view of the increasing demand for new and better materials for present and future aerospace requirements, the Bureau of Naval Weapons (BuWeps) initiated a Refractory Metal Sheet Rolling Program (RMSPR) to develop information necessary to provide sheet materials worthy of the classification of "aerospace quality." The work was programmed into three Phases:

I, determination of the material and process parameters and the production of plate and sheet by the optimum procedures developed;

II, investigation of the mechanical and physical properties to assess the materials for aerospace applications;

III, establishment of plate and sheet product applicability and fabrication techniques.

This report covers an investigation of the mechanical and thermal properties of two refractory-metal sheet materials that were produced in the RMSRP:

(1) tungsten sheet, which was produced from powder compacts by the Fansteel Metallurgical Corp. and

(2) TZM molybdenum alloy sheet, which was produced from arc-melted ingots by Refractomet Division of Universal-Cyclops Steel Corp.

The objective of the program was to provide preliminary design data sufficient to allow consideration of the materials for applications at various temperatures.

SCOPE

The two sheet materials evaluated were furnished by BuWeps. Both the tungsten and TZM sheet were supplied in the optimum condition (warm-worked and stress-relieved) developed in Phase I of the RMSRP. In addition to this condition, specimens from both sheet materials were evaluated in the recrystallized condition, and the TZM sheet was evaluated in the optimum-coated condition. Part of the experimental work included determination of the recrystallization temperatures, which information was then used in treating the as-received materials to obtain the recrystallized specimens. The coatings for the TZM alloy were selected in collaboration with personnel at BuWeps, University of Dayton Research Institute, and the Air Force Materials Laboratory. Evaluation of coated tungsten sheet was deleted from the program upon the recommendation of the Refractory Metal Sheet Rolling Panel because suitable coatings for tungsten were not available. Instead of evaluating both the tungsten and TZM sheet in the optimum-coated condition, as originally scheduled, we evaluated the TZM sheet with two selected coating systems. The coatings selected for the TZM sheet were W-3 (Chromalloy) and PFR-6 (Pfaudler). The static oxidation tests on coated TZM, which were originally scheduled in the program, were conducted by the University of Dayton Research Institute because they have an apparatus for these evaluations that meets the requirements of MAB-189-M, "Evaluation Procedures for Screening Coated Refractory Metal Sheet." This arrangement was made in an effort to coordinate the evaluation of the oxidation resistance of coated TZM sheet with similar work that was performed by the University of Dayton Research Institute for the Air Force Materials Laboratory. The results of the oxidation tests on the TZM are summarized in the final report on AF33(615)1312.

A summary of the various types of evaluations in the program, the test temperatures, and the material conditions are shown in Table I. To the extent possible, the procedures described in Materials Advisory Board Report MAB-192-M, "Evaluation Test Methods for Refractory Metal Sheet Materials,"(1)[a] were used. Originally, all the properties listed in Table I were to be determined from only one gage of each material. However, upon a recommendation by the Refractory Metal Sheet Rolling Panel and after approval by BuWeps, the tensile evaluations were extended to three gages for the TZM and two gages for the tungsten sheet as a practical means to develop some information on the influence of sheet thickness on the mechanical properties. For the tungsten sheet, all of the different types of evaluations were conducted on 0.060-in.-thick sheet with additional tensile evaluations at selected temperatures on 0.100-in.-thick sheet. For the TZM sheet, all of the different types of evaluations were conducted on 0.040-in.-thick sheet with additional tensile evaluations on 0.020- and 0.060-in-thick

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a Numbers in parentheses relate to references in the Bibliography.

Table I

Summary of Property Evaluations

Property	Material	Material Condition[1]	Temperatures, °F
Tensile	TZM	O., R., C.	RT[2], 1200, 2000, 2200, 2500, 3000
	W	O., R.	RT[2], 1200, 2000, 2500, 3000, 3500, 4000, 4500
Compression	TZM	O., R.	RT
	W	O., R.[3]	RT, 600, 750, 900, 1200, 1500, 1800
Tensile Notch Sensitivity	TZM	O., R.	RT and to above the transition temperature
	W	O., R.	RT and to above the transition temperature
Shear Strength	TZM	O.	RT
	W	O.	RT
Bearing Strength	TZM	O.	RT
	W	O.	RT
Tensile Creep	TZM	O.	2000, 2500
	W	O.	2500
Thermal Stability	TZM	O.	RT
	W	O.	RT
Bend Transition Temperature[2]	TZM	O., R., C	As necessary to establish bend transition temp.
	W	O., R.	As necessary to establish bend transition temp.
Fusion Weld Joint Efficiency	TZM	A.W., H.T.	RT, 2500
Density	TZM	O.	RT
	W	O.	RT
Thermal Expansion	TZM	O.	Obtain curve RT to 2500
	W	O.	Obtain curve RT to 2500
Thermal Conductivity	TZM	O.	500, 1200, 1800, 2500
	W	O.	500, 1200, 1800, 2500, 3000
Heat Capacity	TZM	O.	500, 1200, 1800, 2500
	W	O.	500, 1200, 1800, 2500, 3000
Recrystallization	TZM	O.	As necessary to establish recrystallization temp.
	W	O.	As necessary to establish recrystallization temp.
Oxidation[4]	TZM	C.	2500, 2800

[1] O. - optimum, R. - recrystallized, C. - coated, A.W. - as-welded, H.T. - heat treated.
[2] Evaluations made in both transverse and longitudinal orientations; all others in longitudinal orientation only.
[3] Recrystallized specimens evaluated at room temperature only.
[4] Tests performed by the University of Dayton Research Institute and reported in the final report on AF33(615)1312.

sheet. As the program progressed, a number of revisions of the original scope were made, with the approval of BuWeps, to obtain additional data for some properties and to eliminate other evaluations that were not appropriate after preliminary data and other information from this and related programs became available. Besides these relatively minor revisions, the scope of the program was extended to obtain data on the tensile and notched-tensile properties of TZM sheet in : optimum and recrystallized conditions for a statistical analysis of the variation of these properties at different temperatures for different locations within sheets, different sheets, different heats, and different sheet thicknesses. The work performed in the extension is summarized in a separate volume (Part 2) of the final report. (2)

MATERIALS

Tungsten Sheet

The tungsten sheet materials were produced in Phase I of the RMSRP by Fansteel Metallurgical Corporation on BuWeps Contract No. NOw-60-0621-c. The size and identification of each sheet supplied to SRI for determination of the mechanical and thermal properties is shown in Table II.

Table II

Identification and Size of the Tungsten Sheets

Sheet No.	Fansteel Lot No.	Thickness, In.	Length In.	Width, In.	Area, Sq. Ft.
6	A5467	0.055-0.058	46-47.5	21.0	6.7
15	A5467	0.057-0.062	51-53	21.5	7.8
17	A5467	0.059-0.063	53	51.0	7.7
112	A5467	0.099-0.105	32-32.5	19.0	4.2

The available processing information for the tungsten sheet is given in the final report on BuWeps Contract No. NOw-60-0621-c (3). Briefly, the sheets were hot-rolled from sintered sheet-bars that were produced from reduced ammonium paratungstate. The tungsten-powder particle size ranged from about 1.5 to 15 microns in diameter, with a mean diameter between 4 and 5 microns. Table III shows the approximate chemistry of the tungsten

powder used for the sheets.

Table III

Approximate Composition of Tungsten
Powder in Percent by Weight (3)

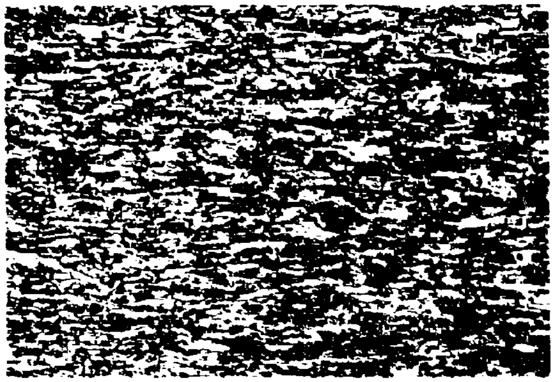
O_2	N_2	Ni	Mn	Mg	Mo	Fe	Al	Si	Cu	Ag	Ca
0.026	0.0005	<0.001	<0.001	<0.001	0.010	<0.001	<0.001	<0.005	0.001	0.001	<0.001

The powders were isostatically pressed at about 35,000 psi into sheet-bars, which were sintered to about 93% of the theoretical density in a hydrogen atmosphere in two steps, at 1700° C (3093° F) for 1 hour and at 2300° C (4172° F) for 9 hours. The resulting 1-in.-thick x 8-in.-wide x 13-in.-long sheet-bars were hot-rolled, about 20% reduction per pass, in about eight passes to about 0.175-in. thick at progressively lower temperatures each pass from 1450° C (2642° F) to 1300° C (2372° F). After the fourth pass the material was process annealed, and after the eighth pass the material was process annealed or stress relieved before additional rolling to 0.100-in.- or 0.060-in.-thick sheet respectively. The 0.100-in. sheet was finished in approximately four additional passes as the heating temperature was decreased from about 1300° C (2372° F) to 1100° C (2012° F). The 0.060-in. sheet was finished from the 0.175-in. thickness in about four roll passes on single sheets at 1250° C (2282° F) down to 1150° C (2102° F) and two additional roll passes at 1050° C (1992° F) on two-sheet packs. Both the 0.100- and 0.060-in.-thick sheets were stress relieved at 1150° C (2102° F) for 10 min or 5 min respectively.

As received at SRI, the tungsten sheets had numerous conditioned areas on the surfaces, but no obvious surface defects were found by visual examination. Figure 1 shows the microstructure in the longitudinal and transverse orientations of the three 0.060-in.-thick tungsten sheets supplied for the program. The microstructure in the longitudinal and transverse orientations of the 0.100-in.-thick sheet is shown near the top of Figure 22. The microstructure of Sheet No. 6 was somewhat coarser than that of Sheets No. 15 and 17, which was probably caused by a difference in the grain size of the sheet bars or of the plate after one of the intermediate annealing treatments. A review of the available information on the production of the tungsten sheet failed to show any significant differences in the processing of Sheet No. 6 from the other sheets. However, the bend-transition data and recrystallized microstructure, to be discussed in later sections of the report, indicate a probable significant difference in this sheet from Sheet No. 15 and 17.

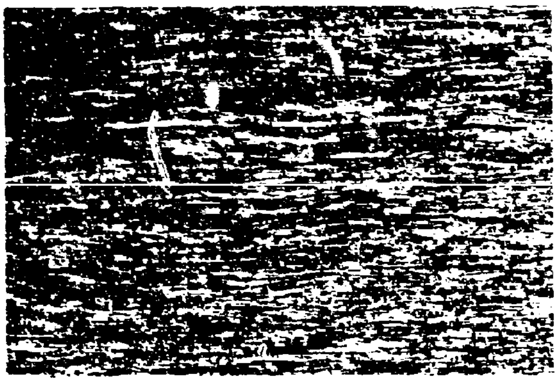
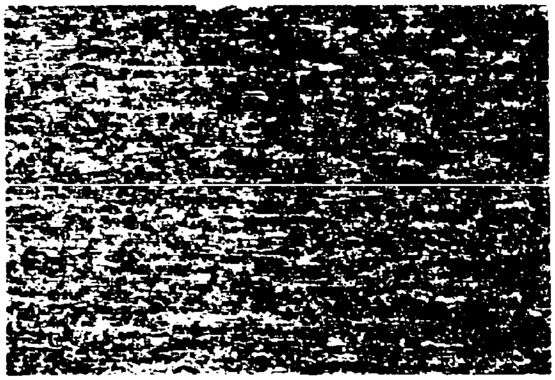

Longitudinal   Transverse

Sheet No. 6

Longitudinal   Transverse

Sheet No. 15

Longitudinal   Transverse

Sheet No. 17

Figure 1. The microstructure in longitudinal and transverse orientations of the 0.060-in. thick tungsten sheet in the optimum condition.

Magnification: 100X   Etchant: $K_3Fe(CN)_6$

Specimen blanks were cut from different locations in the three 0.060-in.- and the one 0.100-in.-thick tungsten sheets to systematically sample each sheet, insofar as practical, for the different evaluations.

TZM Sheet

The TZM sheet materials were produced by the Refractomet Division of Universal-Cyclops Steel Corporation on BuWeps Contract No. NOas 59-6142-c. The size and identification of each sheet is shown in Table IV.

Table IV

Identification and Size of the TZM Sheets

Sheet No.	Universal-Cyclops Lot. No.[1]	Thickness, In.	Length, In.	Width, In.	Area, Sq. Ft.
55	10	0.037-0.043	64	24	10.68
56-1	10	0.037-0.043	15 7/8	24	2.67
56-2	10	0.037-0.043	48	24	8.00
74	13	0.018-0.022	12 1/2	23 7/8	2.07
23	5	0.057-0.063	12 1/2	24	2.08

[1] All of the different lots were from Heat No. KDTZM 1196.

A summary of the composition, manufacturing processes, and release properties for all the TZM sheets used in the program is shown in Appendix A. The TZM sheet was produced from an 8-in. diameter arc-melted ingot, which was extruded to a 4.5-in.-diameter round at 2100° F. The resulting round slab was annealed for 1 hour at 2800° F and forged in "Infab"[b] at 3400° F to 1.5-in.-thick sheet bars. The sheet bars were annealed at 2800° F for one hour and longitudinally rolled at 2200° F in two intermediate reductions and finally cross-rolled at 1800° F to within 0.004 to 0.008 in. of the final thickness. The sheets were annealed at 2700° F and 2150° F respectively after the first and second longitudinal rolling operations. Each gage was stress-relieved

b "Infab" is a facility for processing metals in an inert atmosphere. The facility was built and is operated by Universal Cyclops Steel Corporation under a Navy contract.

at 2300° F after cross-rolling and finished to the final thickness by belt grinding and pickling. Table V shows the chemistry of each sheet furnished for evaluation.

The TZM sheet materials, as received at SRI, appeared to be in excellent condition, and no serious surface defects were found by visual examination. The microstructure on longitudinal and transverse sections from the different gages of the as-received TZM sheets are shown in Figures 44, 45 and 46.

The two 0.040-in.-thick TZM sheets, No. 55 and 56, were sampled equally for the different types of mechanical-property evaluations.

PREPARATION OF SPECIMENS

The specific specimen designs used for the different types of evaluations will be discussed and shown in a later section of the report on the testing procedures. Where possible, the specimens conformed to those recommended in Materials Advisory Board Report MAB-192-M (1).

The preparation of all specimens was accomplished by SRI with conventional machining and grinding equipment. The gage section of specimens for the mechanical-property evaluations were ground with a surface grinder and finished by hand polishing with "00" abrasive paper.

Pin-type gripping was used, where possible, for the tensile, bearing, shear, and creep specimens. Loading holes (3/8-in. dia) were drilled in these specimens with carbide drills and a special holding fixture in which the specimen blanks were clamped. The drilling process involved three steps: (a) rough drilling with an undersize drill; (b) finish drilling; (c) deburring with fine abrasive. Shoulded-loaded specimens were used in evaluation of the tungsten materials under conditions where pin-loaded specimens failed at the loading holes rather than in the gage section.

Ipsenlab of Rockford, Inc., recrystallized the tungsten and TZM specimens required for the tensile, notched-tensile, compression and bend-transition evaluations in the recrystallized condition. The specimens were recrystallized in a vacuum of 5×10^{-4} torr or better at time-temperature conditions selected by SRI from data developed in the present investigation. The recrystallization treatments for the two materials investigated were:

Material	Temp, °F	Time at temp, hr
Tungsten	2550	1
TZM	2475	1

Table V

Composition of TZM Materials Received For Property Evaluation

Sheet No.	Nominal Thickness in.	Lot No.	Element, % C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
74	0.020	13	0.032	0.42	0.088	<0.0035	0.0018	<0.001	0.0042	0.0003	0.0001
35	0.040	10	0.030	0.49	0.104	<0.001	<0.0015	0.002	0.0012	0.0003	0.00017
56[1]	0.040	10	0.031	0.50	0.119	<0.0035	<0.0015	<0.001	0.0015	0.0002	0.00024
23	0.060	5	0.024	0.50	0.083	<0.0035	<0.0015	<0.001	0.0022	0.0010	0.0002

[1] Sheet No. 56 was received in two pieces labled 56-1 and 56-2. The chemistry is the same for both pieces.

TZM specimens for determination of the bend-transition temperature and the tensile properties in the optimum-coated condition were prepared for coating by SRI and submitted to the University of Dayton Research Institute for coating application by the coating vendors. The University of Dayton Research Institute coordinated the application of the coatings for the bend and tensile specimens, for evaluation by SRI, with the coating of the specimens for the oxidation tests that they performed relative to Contract No. AF 33(615)1312. The coating systems selected for evaluation were PFR-6 and W-3, which are proprietary pack-cementation processes of The Pfaudler Company and Chromalloy Corp. respectively. The procedure used by SRI to prepare the tensile and bend specimens for coating by both systems was as follows:

a. Long edges of bend specimens and edges of the gage section of the tensile specimens were draw-filed and polished with 240 grit paper to a full radius.

b. Etched in an aqueous solution of 50% HNO_3 and cleaned in a solution of 4.2 gms of chromic acid in 88 ml of water and 12 ml H_2SO_4.

c. Inspected and additionally polished with 240 grit paper if necessary to remove any flat areas or other imperfections on the edges of the specimens.

d. Re-etch and clean conditioned specimens as outlined in Step b.

Since the purpose of the tests of the coated materials was to determine the effect of the coating on the room- and elevated-temperature properties (in vacuum) and not to determine the protective capability of the coatings, no attempt was made to prepare the ends of the bend specimens or the shoulders of the tensile specimens to remove sharp edges or other surface defects which would normally cause failure of the coatings. Application of the PFR-6 coating caused the specimen thickness to increase 0.0074 in. (0.0037 in. on each side) while the W-3 coating resulted in an increase of 0.0022 in. in thickness of the specimen.

Westinghouse Electric Company, Astronuclear Laboratory, made TIG welds on the 0.060-in. tungsten sheet and the 0.040-in. TZM sheet and electron-beam welds on the TZM sheet for evaluation of the weld joint efficiency. The TIG welding was accomplished in a high-purity helium atmosphere while the electron-beam welding was done in a vacuum of 10^{-5} torr. The specimens were machined after welding.

EQUIPMENT

Most of the facilities that were used for the mechanical- and thermal-property evaluations have been described in detail in numerous publications and reports on similar work for various governmental agencies and industrial concerns (4-20).

Two universal testing machines, with different full-scale load capacities from 3,000 to 120,000 lb, equipped with X-Y and autographic load-deformation recorders plus strain-rate control instrumentation, were used to evaluate the tensile, compression and bend properties. A special screw-driven tensile machine, developed at SRI, was used in the bearing, shear and notch-tensile work. This machine is capable of straining specimens to failure at rates from 5×10^{-6} to 60 in./in./min over a temperature range of -320 to 6000° F. The design features of the machine have been described in detail in WADC TR57-649 Part I and other reports and publications (4,6). A photograph of this machine is shown in Figure 2. Vacuum chambers, inert atmosphere devices, cold chambers, controlled-rate heating units, and high-temperature extensometers were available for use, as needed, with the machines described above. Special fixtures, which are discussed later in the report, were used in conjunction with the testing machines as required to conduct the mechanical-property evaluations.

A Satec creep-rupture machine, equipped with a vacuum chamber and appropriate instrumentation for automatically recording temperature and time-deformation curves, was used for the creep tests. With this machine specimens were loaded by weights, which act through a lever arm (20:1 ratio).

Two vacuum systems were used in the determination of the different properties at high temperatures. A "High Vacuum Equipment Corp." unit was used in conjunction with the universal testing machine and the creep machine to determine the elevated-temperature tensile and creep properties. This system is capable of maintaining a chamber pressure of 10^{-4} torr at temperatures up to 3500° F. Specimens were heated in the split-type vacuum furnace by radiation from tantalum-sheet heating elements. The furnace has a sighting port and thermocouple inlets for monitoring and controlling the temperature. A photograph of this system as used with the universal testing machine is shown in Figure 3. A second vacuum system, built by the Kinney Division of the New York Air Brake Company, was used for the determination of the recrystallization temperatures. This system is capable of maintaining a chamber pressure in the range of 10^{-6} torr. Specimens can be heated in this system by radiation to approximately 3500° F or to their melting temperatures by self-resistance. In the determination of the recrystallization temperatures, the specimens were heated by self-resistance. This chamber, like the other unit, has a sighting port and a number of thermocouple inlets. The system is shown mounted on the special

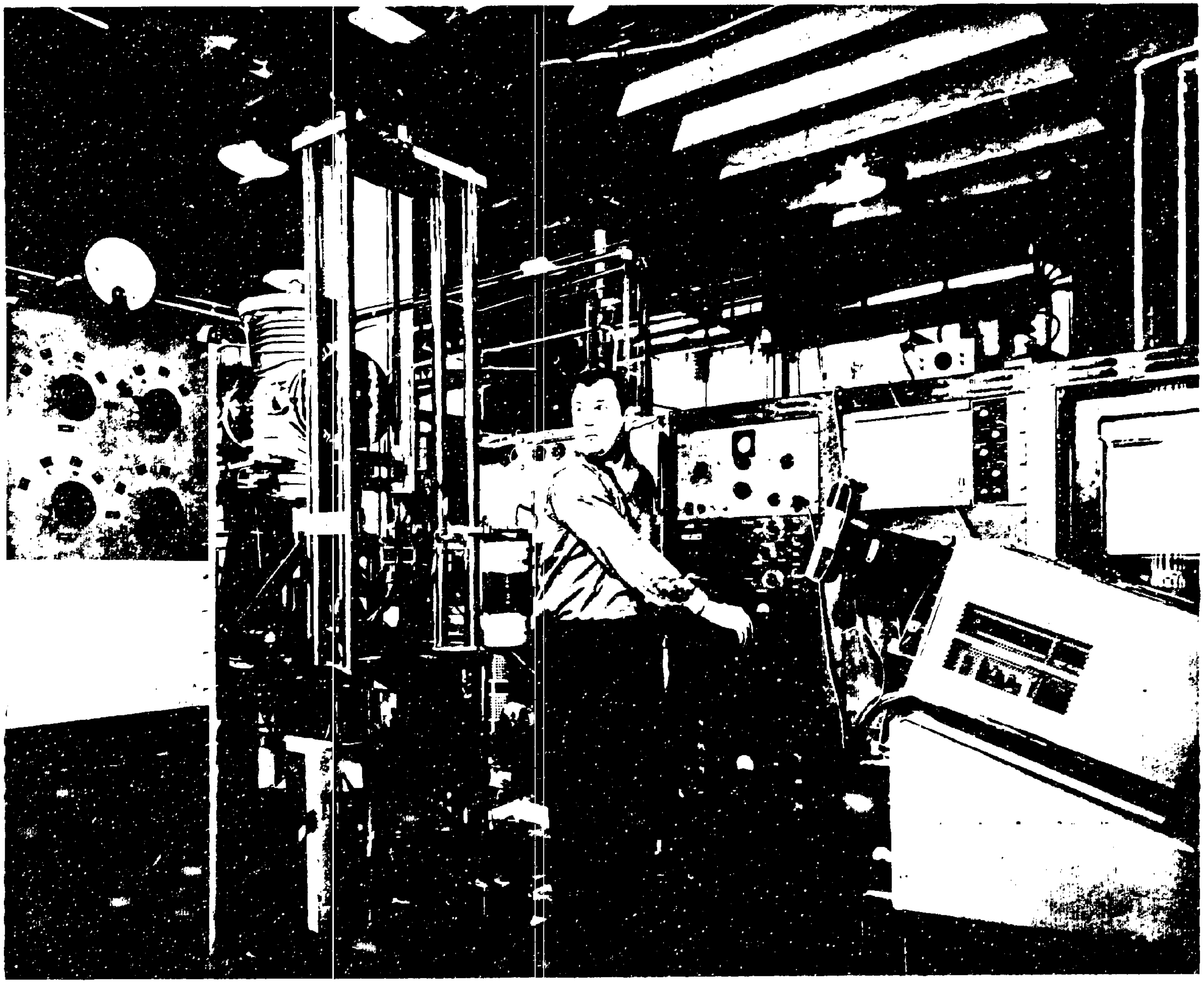


Figure 2. Special tensile apparatus capable of wide range of strain rates, heating rates, and evaluation temperatures.

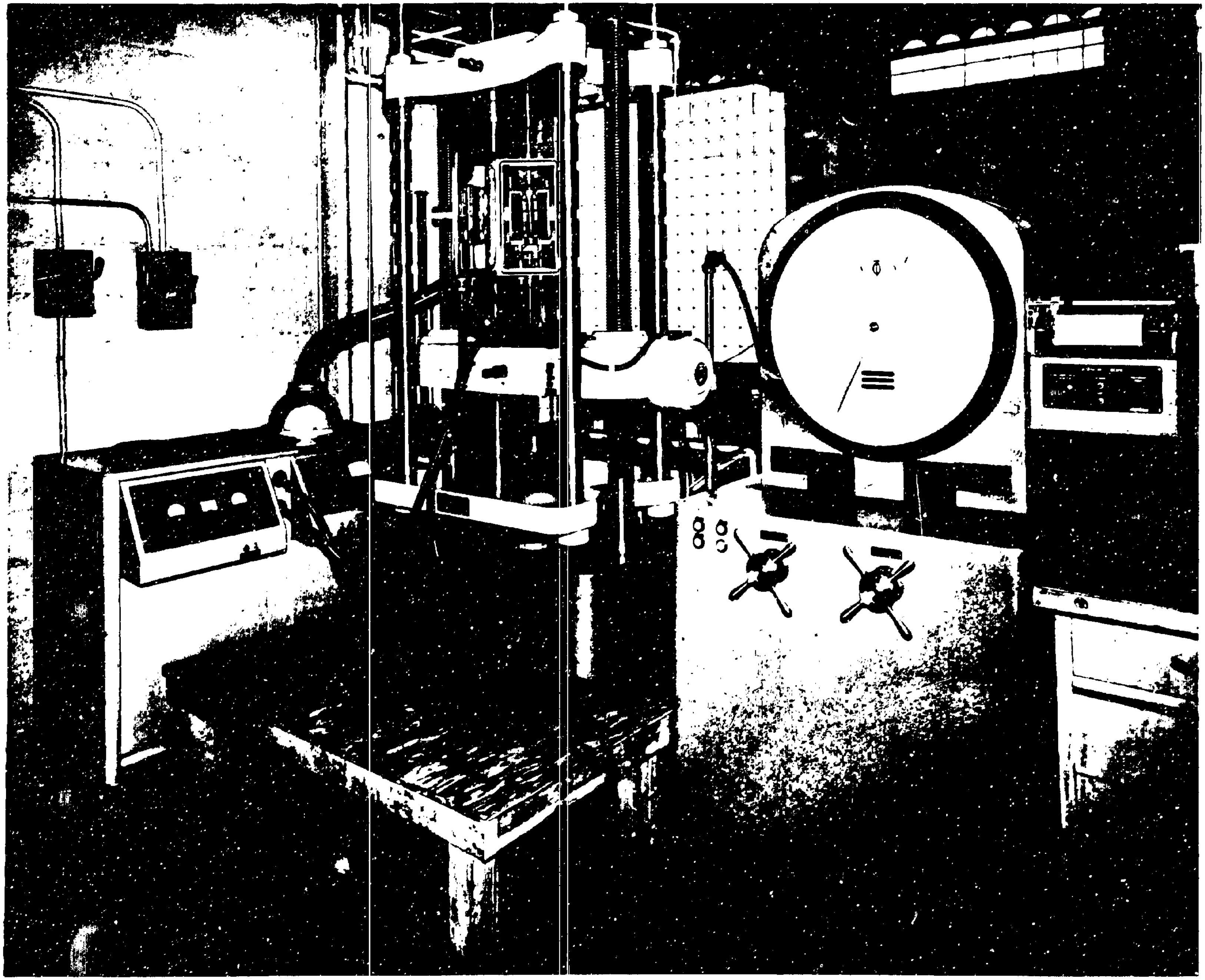


Figure 3. Vacuum furnace system and universal testing machine for tensile evaluations up to 4000° F.

tensile machine in Figure 2 and as used in determination of the recrystallization temperatures in Figure 4.

A Bausch and Lomb Research Metallograph was used for the metallographic examinations and to obtain the photomicrographs.

DPH hardness tests were conducted with a Tukon Tester with a load of 3 kg for the tungsten sheet and 1 kg for the TZM sheet. Other standard Rockwell hardness testers were used for the measurement of surface hardness.

The determination of thermal conductivity up to 1500° F was made with a comparative rod apparatus in which Armco Ingot Iron was used as a conductivity reference. This apparatus has been described in detail in the final report (15) for the program on Air Force Contract AF33(657)-8594. A radial inflow apparatus was used to determine thermal conductivity from 1500° F to 2500° F for the TZM sheet or to 3000° F for the tungsten sheet. The radial-inflow equipment has been described in the final report (16) on Contract No. AF33(657)-11298.

The heat capacities were determined to 1000° F with an adiabatic calorimeter and from 1000° F to 2500° F, for the TZM sheet, or to 3000° F for the tungsten sheet, with an ice calorimeter. Both apparatuses are described in references 15 and 16 in the Bibliography.

The thermal expansions of the tungsten and TZM sheet were determined from 70 to 1000° F with a quartz-tube dilatometer and from 1000 to 2500° F with a graphite dilatometer. Expansions were measured with mechanical dial gages which could be read to 0.0001 in. (0.00004 in./in.).

TEST PROCEDURES

Recrystallization

For determination of the recrystallization temperatures, tungsten and TZM strip specimens, 3/8 in. wide x 7 in. long as shown in Figure 5, were resistance heated in a vacuum of 1.5×10^{-4} torr to temperatures between 1800 and 3200° F and held at temperature for 5 or 60 minutes. The heating time to the different holding temperatures was approximately 5 min. Specimen temperatures up to 2100° F were measured by chromel-alumel thermocouples, and above 2100° F the temperatures were measured with an optical pyrometer. Corrections were made in the optical pyrometer readings for the emissivity of tungsten or molybdenum and for adsorption by the glass viewing port of the vacuum chamber. These corrections were rechecked and verified after the tests were completed by simultaneously measuring the temperature of the specimen

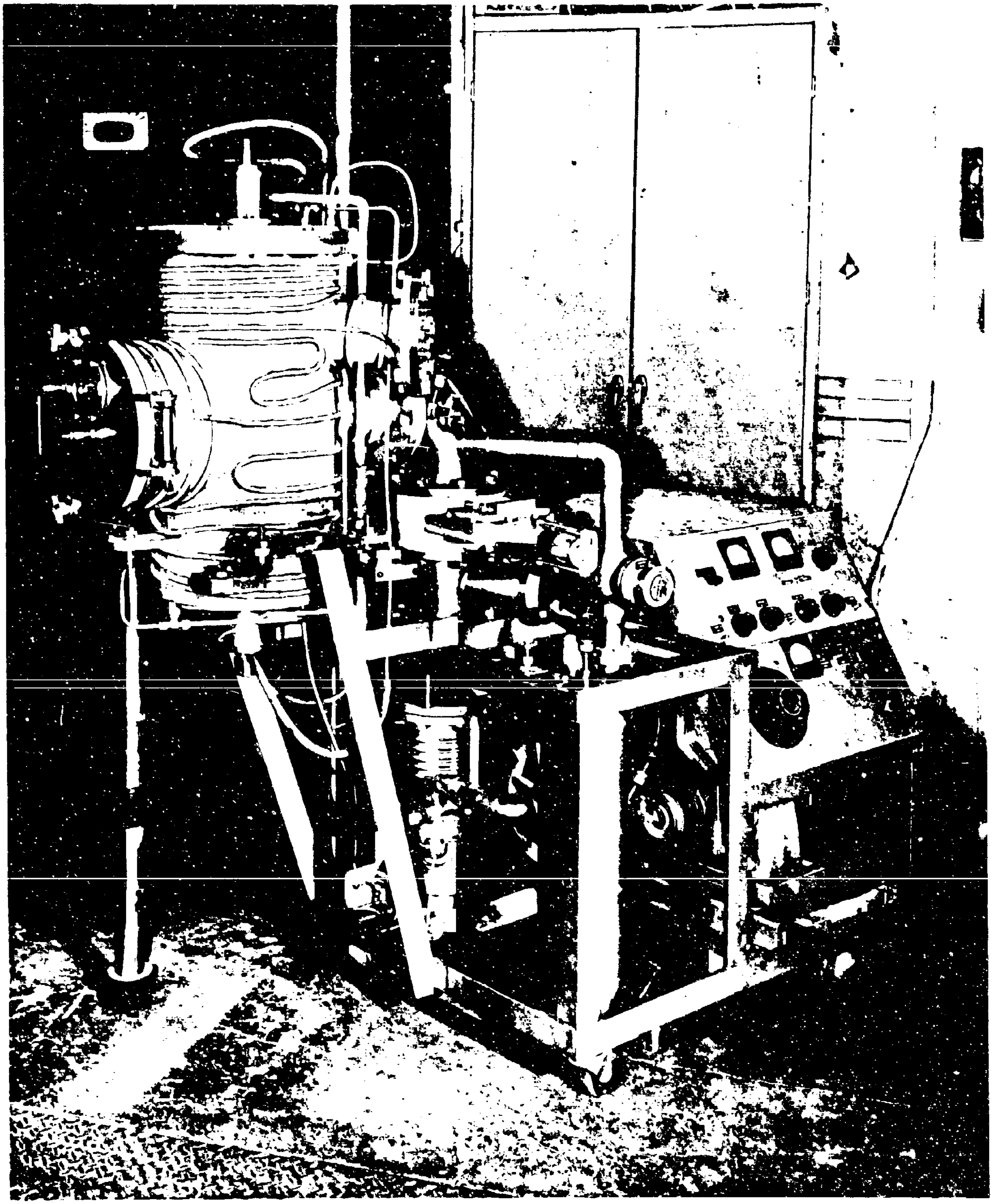


Figure 4. Vacuum chamber and pumping system for use in recrystallization, heat treatment, and creep-rupture evaluation of refractory metal

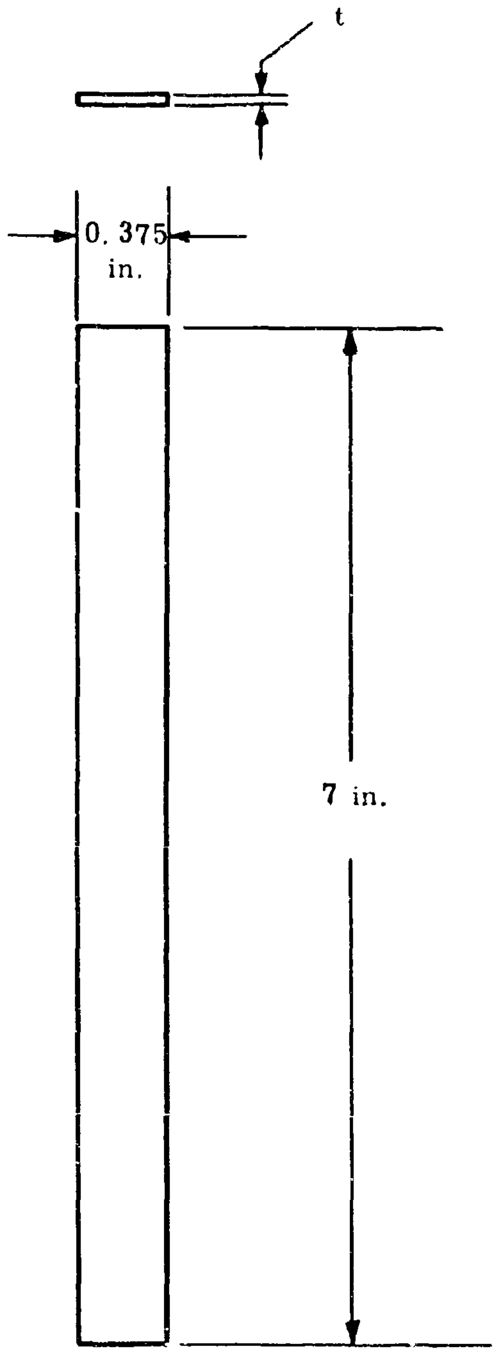


Figure 5. Recrystallization specimen.

with the optical pyrometer and with W-5%Re vs W-26%Re thermocouples. A manually controlled high-current heating unit was the source of power.

The R_c hardness of the 0.060- and 0.100-in. tungsten sheet was measured on the surface of the specimens. In addition, the DPH at the mid-thickness of the sheet and metallographic estimates of the percentage of recrystallized structure were determined to establish the recrystallization characteristics of the different sheets. Two observers independently estimated the percentage of recrystallization, and the results of these independent observations were averaged to determine the reported values. Determination of the recrystallization characteristics of the 0.060-in.-thick sheet was based mainly on results from Sheet No. 15; however, the recrystallization behavior of Sheet Nos. 6 and 7 were checked with that of Sheet No. 15 at five different time-temperature combinations.

The R_a hardness of the 0.040-in. and 0.060-in. TZM sheet and the Rockwell 15-T hardness for the 0.020-in. TZM sheet were measured on the surface of the specimens. The procedures for determining the DPH and metallographic estimates of the percentage of recrystallization were the same as those described for the tungsten sheet. Determination of the recrystallization parameters for the 0.020-in., 0.040-in. and 0.060-in. TZM sheet were based primarily on the results from Sheet Nos. 74, 55, and 23 respectively; however, the recrystallization behavior of the 0.040-in. Sheet No. 56 was checked with that of Sheet No. 55 at different temperatures.

In general, the recrystallization temperature of the tungsten and TZM sheet were determined by metallographic and hardness measurements, as outlined in MAB-192 (1).

Tensile

Tensile evaluations were conducted on both tungsten and TZM materials to (a) determine the tensile properties at room- and elevated-temperatures, (b) determine the notched-tensile strength at room temperature, (c) evaluate the thermal stability of creep-strained materials, and (d) evaluate fusion-welded joint efficiencies (TZM only). The effect of temperature on the tensile properties of the two materials in the optimum, recrystallized, and optimum-coated (TZM only) conditions was determined principally with the equipment described earlier. Duplicate, or triplicate, tensile specimens were evaluated at each temperature shown in Table I according to the specifications of MAB-192-M (1). Sketches of the unnotched specimen configurations for the room-temperature and elevated-temperature evaluations are shown in Figure 6. The shoulder-loaded specimen was used for the room- and moderately elevated-temperature tensile evaluations where the pin-loaded specimens fractured across the shoulders. Specimens

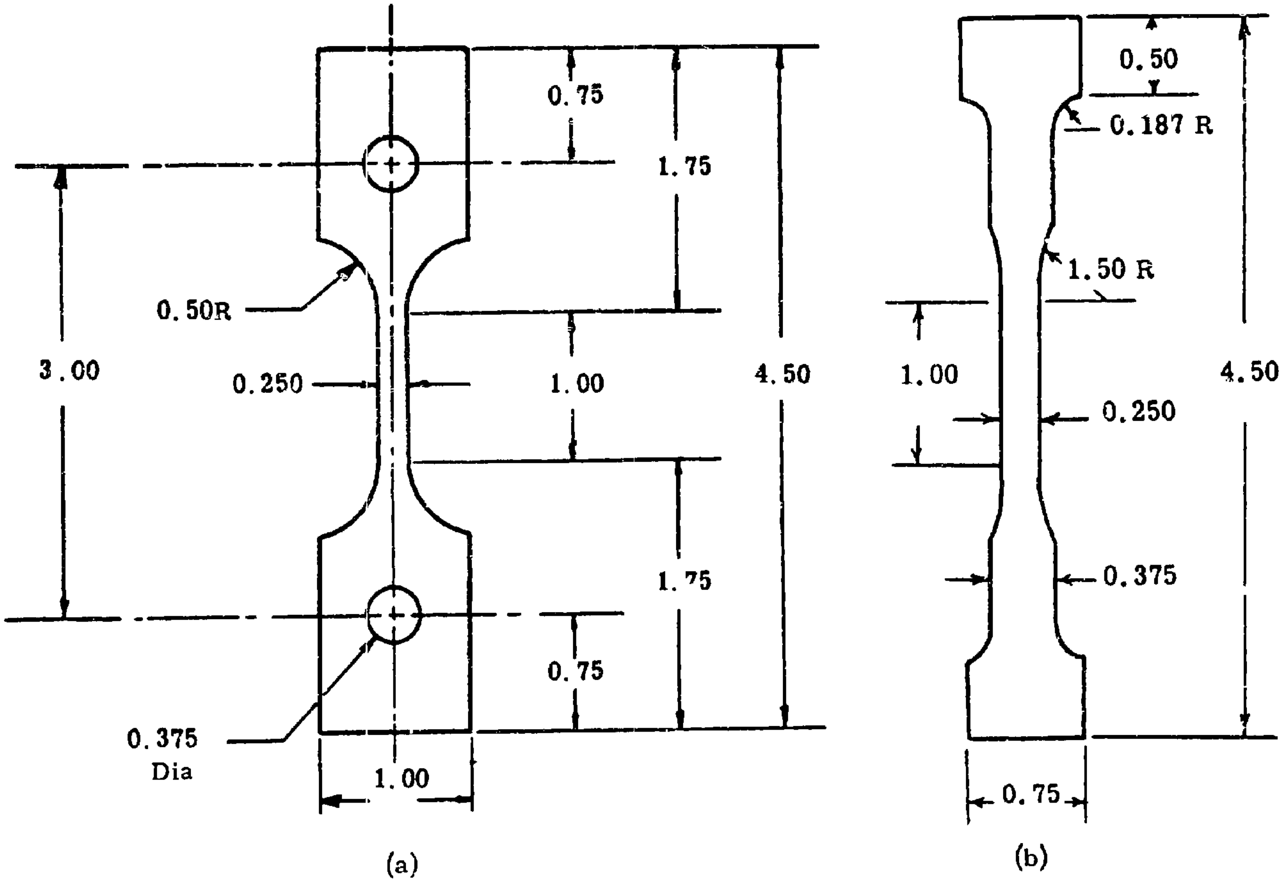


Figure 6. Specimens for tensile and creep tests.[1]

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[1] The shoulder-loaded specimen (6b) was used only for tensile tests on the tungsten sheet at temperatures where the pin-loaded specimens (6a) tended to fracture across the section at the loading holes.

were heated to temperature in approximately 30 minutes in a vacuum of 5 x 10^{-4} torr or better by radiation from tantalum elements, held 15 minutes at temperature, and then strained to failure at controlled rates. At room temperature and 1200° F the strain rates were 0.005 min^{-1} to 0.6% offset and 0.05 min^{-1} to fracture. For evaluations at 2000° F and higher, the strain rate was approximately 0.05 min^{-1} throughout the tests. Temperatures were measured with chromel-alumel thermocouples, attached to the specimen, up to 2000° F and by an optical pyrometer or W-5%Re vs W-26%Re thermocouples at higher temperatures. The heating unit was manually controlled. Corrections for the emissivity of tungsten or molybdenum and for absorption by the glass viewing port of the vacuum furnace were made in the optical temperature measurements.

Strain during the elevated-temperature evaluations was detected by strain-gage extensometers clipped onto the water-cooled pull-rods of the furnace chamber. Stress was sensed by a strain-gage load cell. Excitation was supplied to the extensometer and load cell bridges from a stable 5000 cps AC source. The outputs from the two bridges, which were proportional to strain and stress, was amplified, demodulated, filtered, and fed as a DC signal into the X (strain) and Y (stress) axis of an X-Y recorder. Application of the extensometer at the pull-rods, rather than at the specimen gage points, for evaluations at elevated temperatures introduced a slight error into the strain measurements. This error necessitated correcting the modulus-of-elasticity values, but did not significantly affect the determination of other tensile properties. The required correction factors for the moduli of the two materials were determined from room-temperature modulus values obtained with a conventional differential-transformer extensometer (Class B-1 per ASTM E 83-57T) over a 1.0-in. gage length. The correction as applied to the reported moduli was the ratio of apparent elastic modulus, obtained with the extensometer attached to the pull-rods, to the elastic modulus obtained with the conventional extensometer attached at the gage points of the specimens.

The 0.2%-offset yield strength, ultimate tensile strength, and modulus of elasticity was determined from the recorded stress-strain curves. The total elongation and reduction of area, where possible, were measured from the fractured tensile specimens.

Notched Tensile

Notched-tensile evaluations were conducted at different temperatures on the tungsten and TZM sheet in the optimum and recrystallized conditions to establish the brittle-to-ductile transition temperature. The notched specimens had a major width of 0.500-in., 60° notches with 0.010-in. radii, and a notch-to-notch width of 0.250-in., which produced a stress concentration factor, K_t,

of 4.2. The notched specimen is shown in Figure 7. Unnotched tensile specimens were tested at each temperature where notched specimens were tested in order to determine the notched-strength ratio. For the tungsten sheet, the temperature range over which the notched tensile tests were performed was from 200° F through 900° F; for the TZM, the temperatures at which notched specimens were tested were from -200° F through room-temperature. The tungsten notched-tensile specimens were heated to temperature in approximately 15 minutes, held 5 minutes at temperature, and strained to fracture at a cross-head rate of approximately 0.005-in. min^{-1}. The TZM specimens were cooled by metering low-temperature nitrogen gas, by means of a manually operated valve, into a cryostat that surrounded the specimen. The nitrogen gas was cooled by passing it through a copper coil immersed in liquid nitrogen in a vacuum flask. Approximately 5 min were required to cool the specimens to the desired temperature, after which they were strained to fracture at a cross-head rate of approximately 0.005 in. min^{-1}. For both the elevated- and low-temperature tests the temperature of the specimens was measured by thermocouples, held in contact with the surface of the specimen, and a nul-balance potentiometer.

Bend-Transition Temperature

Evaluations of the bend properties for both the longitudinal and transverse directions of the 0.060-in. tungsten sheet and the 0.040-in. TZM sheet in the optimum, recrystallized and coated (TZM only) conditions were conducted in accordance with the recommendations of MAB-192-M (1). A bend fixture, shown in Figure 8, was used in conjunction with a universal testing machine for these evaluations. Punches with radii of 1.5, 4, and 8 times the sheet thickness (1.5t, 4t, 8t) were used to evaluate the tungsten specimens, and a punch radius of 4t was used to evaluate the TZM specimens. The distance between the anvils was 1.50-in. for the 0.060-in. tungsten and 1.25-in. for the TZM sheet. Figure 9 shows the dimensions of the bend specimens. The criterion for the definition of the bend-transition temperature range was the minimum temperature at which a 90° bend could be made without cracking, at a given punch diameter, and highest temperature at which a 90° bend could not be made without cracking. The test temperature range was 300° F to 700° F for the tungsten sheet and -220° F to 200° F for the TZM sheet. The elevated-temperature-bend specimens were heated by tungsten-element radiation lamps, which were controlled by small chromel-alumel thermocouples in contact with the bottom surface of the specimen. A thermocouple attached to the punch was used to measure and control the temperature of the punch tip. For evaluations below room temperature, gaseous nitrogen, which was cooled in a copper coil immersed in liquid nitrogen, was used to cool the specimen and fixture to the desired temperature. The flow of nitrogen gas into an insulated chamber that surrounded the specimen

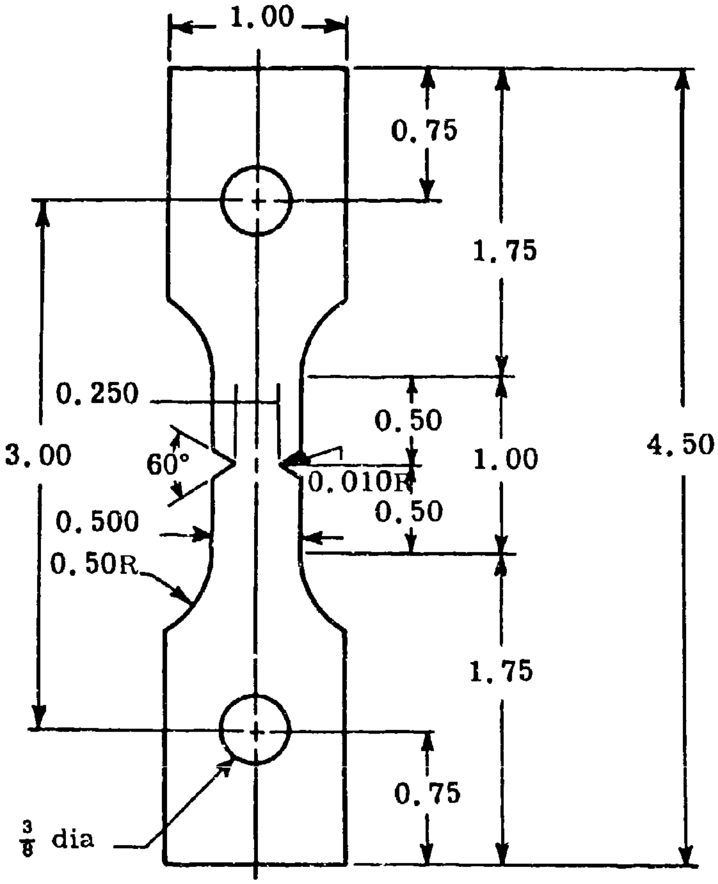


Figure 7. Notched tensile specimen with a stress concentration factor, K_t, of 4.2.

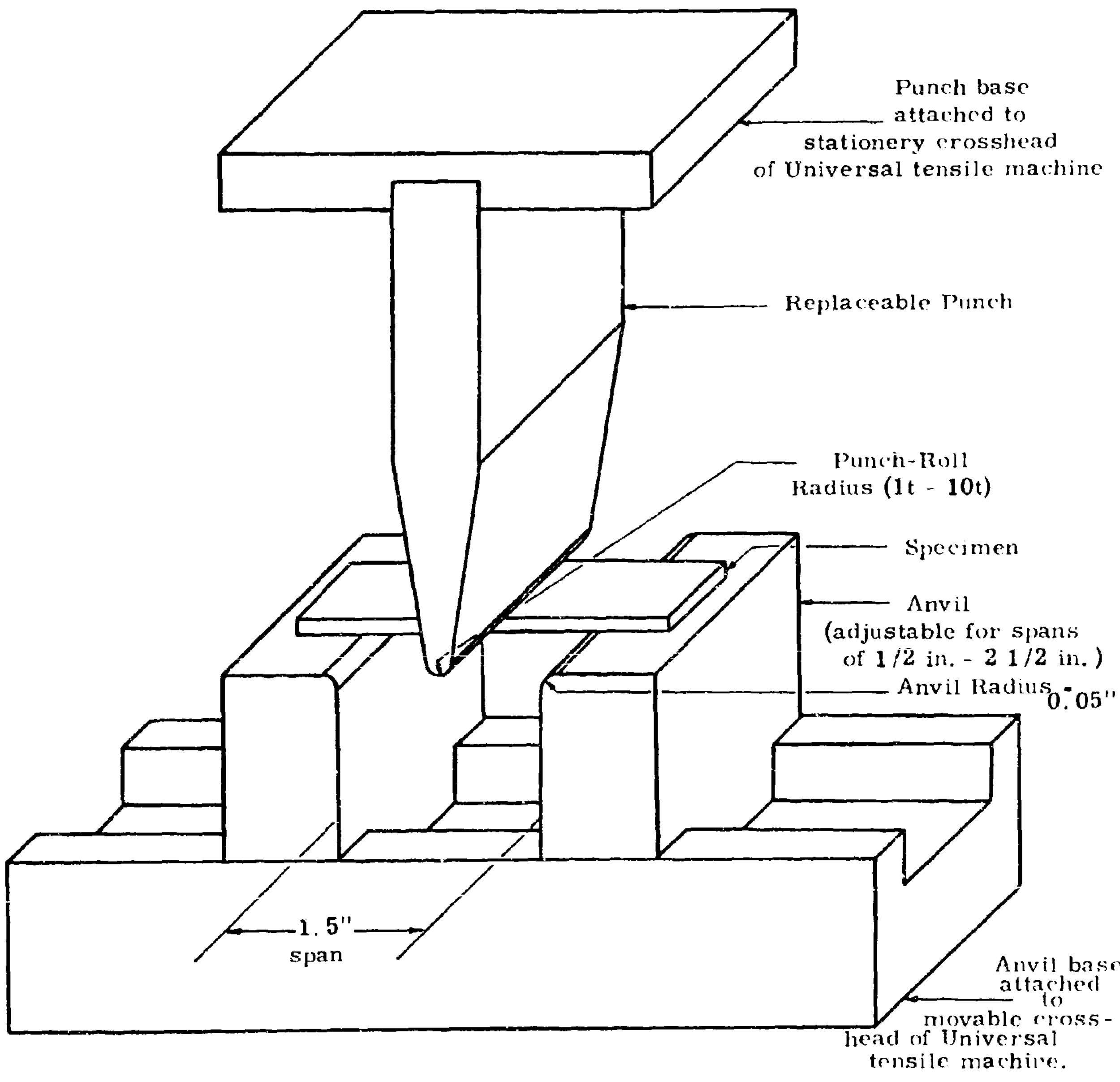


Figure 8. Bend-test fixture.

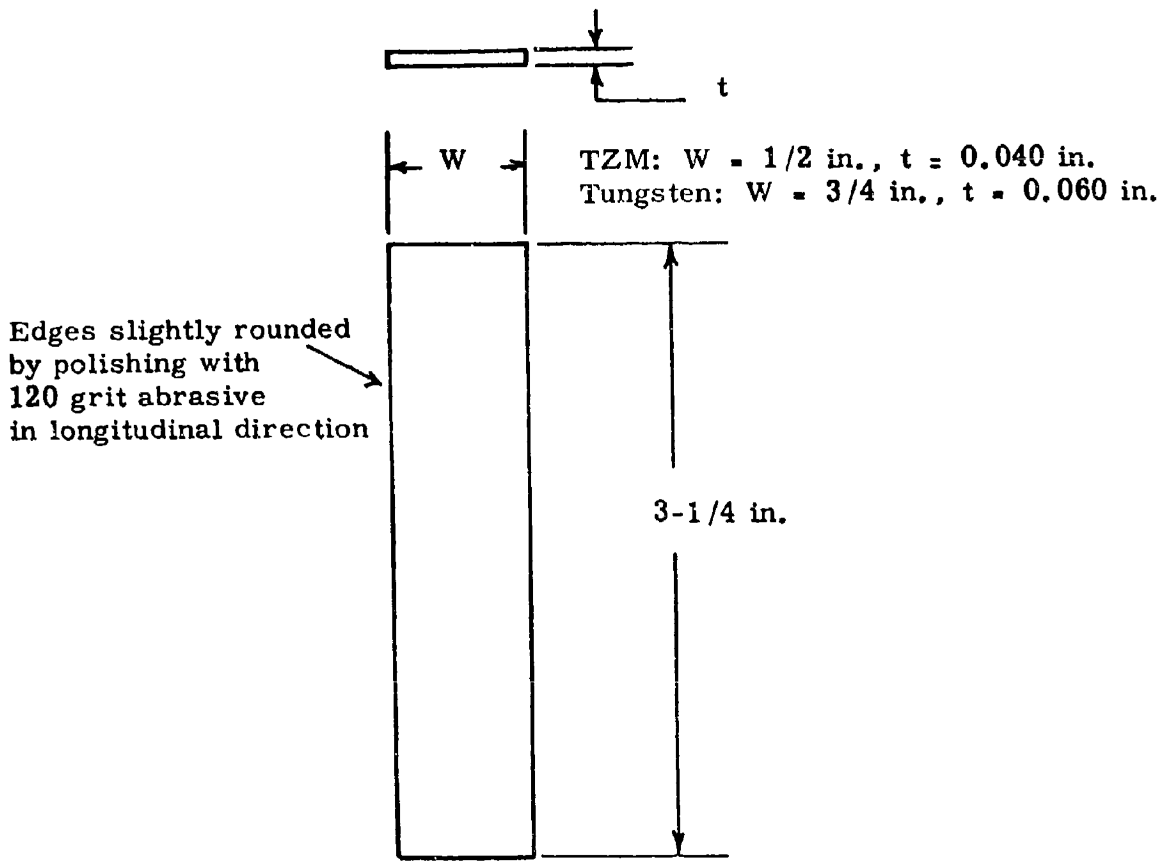


Figure 9. Bend specimen.

and fixture was controlled by a solenoid valve, which was actuated by a chromel-alumel thermocouple attached to the specimen, and a temperature controller. All specimens were held at temperature approximately 10 minutes before bending at a deflection rate of 1.0 in./min. A mirror, which was positioned under the specimen between the anvils of the fixture, was used to observe the surface of the specimen during the tests. The surface of the specimens that were bent 90° without apparent fractures were examined with a magnifying glass to determine if fine cracks existed. The bend angle at the first indication of fracture was calculated from the geometry of the fixture and the displacement of the punch.

Compression

Compression evaluations were conducted at room temperature from both longitudinal and transverse orientations for the 0.060-in. tungsten and 0.040-in. TZM sheet in the optimum and recrystallized conditions. A sub-press was used with the universal testing machine to provide bending restraint and to axially load the specimens. Sketches of the fixture and specimen configuration used in the compression determinations are shown in Figures 10 and 11 respectively. Support blocks, which were polished and lubricated to minimize friction, were used to prevent buckling of the specimens. Strain was measured at the gage-point lugs with a strain-gage extensometer, and load was measured with the weighing systems of the universal testing machine. A stress-strain curve was recorded, up to 0.6% offset, with an X-Y recorder. The strain rate for these tests was approximately 0.005 min^{-1}. In general, the procedure and apparatus used for these evaluations meet the requirements of ASTM Specifications E9-52T and E209-63T.

A few elevated-temperature-compression evaluations were conducted to obtain data needed by Solar in the performance of contract No. NOw 63-0786d, which is part of Phase III of the RMSRP. A total of sixteen compression test specimens, five each from the 0.020- and 0.060-in. and six from the 0.100-in. RMSRP tungsten material were fabricated by Solar as shown in Figure 12. This specimen configuration was designed to stand without lateral support between the platens of the compression fixture. Although there are some disadvantages with this particular specimen geometry, it permits the evaluation of tungsten sheet at elevated temperatures without prohibitive, elaborate heating and lateral-support apparatus. The compression specimens were evaluated at temperatures of 600° F and 750° F, 900° F and 1500° F, and 1200° F and 1800° F for the 0.020-in., 0.060-in., and 0.100-in. tungsten sheet respectively. Specimens were heated to temperature in approximately 20 minutes in an argon atmosphere by a split-muffle type radiation furnace, held 10 minutes at temperature, and then strained to 0.6% offset at a controlled rate of approximately 0.005 min^{-1}.

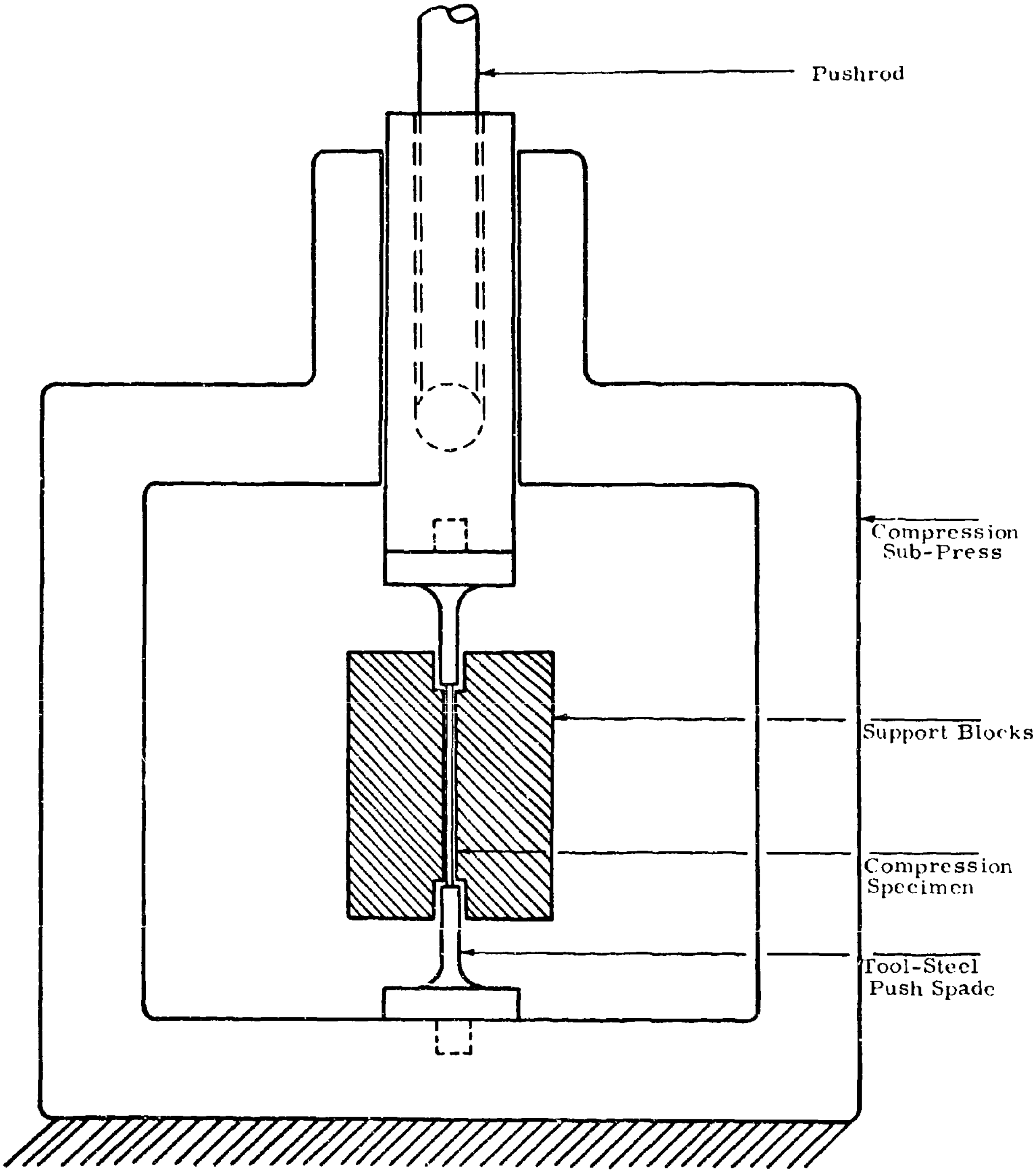


Figure 10. Compression fixture showing cross-section of the support blocks with specimen in place.

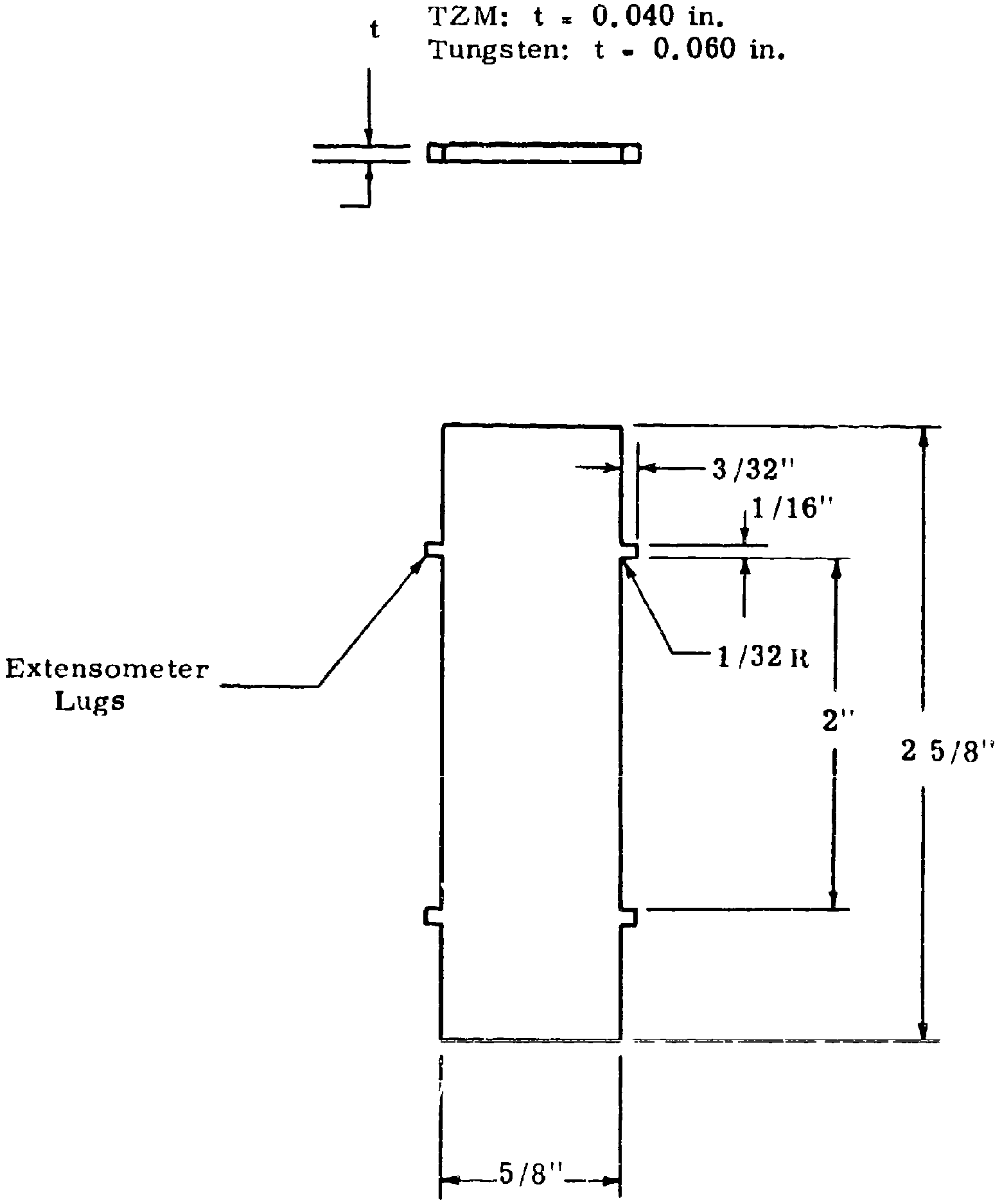


Figure 11. Compression specimen.

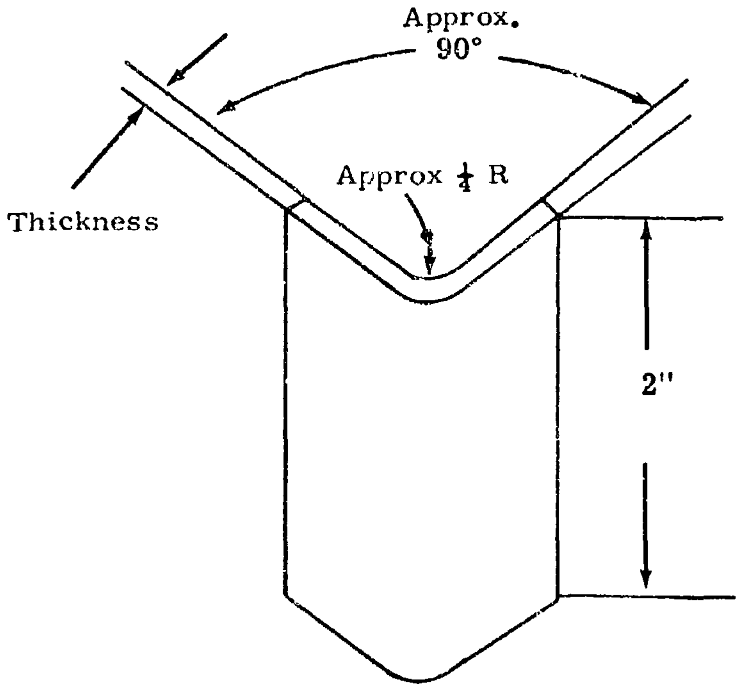


Figure 12. Compression specimen for use at elevated temperatures.

Bearing

Bearing evaluations were conducted on longitudinally oriented specimens of the 0.060-in. tungsten and 0.040-in. TZM sheet in the optimum condition to determine the bearing ultimate strength and yield strength at 2% deformation of the bearing hole. The area on which these strengths are based is the product of the bearing hole diameter and the sheet thickness. A specimen with an e/D ratio of 1.5, as shown in Figure 13, was used for the evaluations. The tungsten specimens were evaluated at 300° F and 400° F and the TZM specimens at room temperature. For the elevated-temperature evaluations the specimens were heated with radiation lamps, which were automatically controlled by a potentiometer controller actuated by a signal from a chromel-alumel thermocouple attached to the specimen. Load versus bearing-hole deformation was recorded with an X-Y recorder as sensed by a strain-gage load cell and extensometer. Specimens were loaded to failure at a crosshead speed of 0.005 in. min^{-1}.

Shear

Evaluations to determine the ultimate shear strength were conducted at room temperature on the 0.040-in. TZM and at 400° F on the 0.060-in. tungsten in the optimum condition. All specimens were machined so that the shear plane was in the longitudinal direction. The specimen design used for both materials is shown in Figure 14. The shear test section was 3/16-in. long defined by two 1/16-in.-diameter holes spaced 1/4 in. apart on the axis with two offset slots at 45° to the axis. For the tests at 400° F the specimens were heated by radiation lamps and the temperature was measured and controlled by thermocouples that were flash welded to the surface near the shear plane. The specimens were loaded to fracture at a crosshead speed of 0.005 in. min^{-1}.

Creep

Creep evaluations at 2500° F for the tungsten sheet and at 2000° F and 2500° F for the TZM sheet were conducted on longitudinally orientated specimens of the materials in the optimum condition. The specimen design was the same as that used for the tensile tests as shown in Figure 6(a). All tests were performed in a vacuum furnace at a pressure of approximately 1×10^{-4} torr. Specimens were heated to temperature in approximately 20 minutes by radiation from tantalum heating elements, held 10 minutes, and then loaded to different stress levels selected to produce 1% total deformation in approximately 100 hours. A constant load was maintained on the specimens through the lever-arm system of the creep machine. Temperature was automatically controlled and recorded by a temperature-control instrument actuated by a signal from a

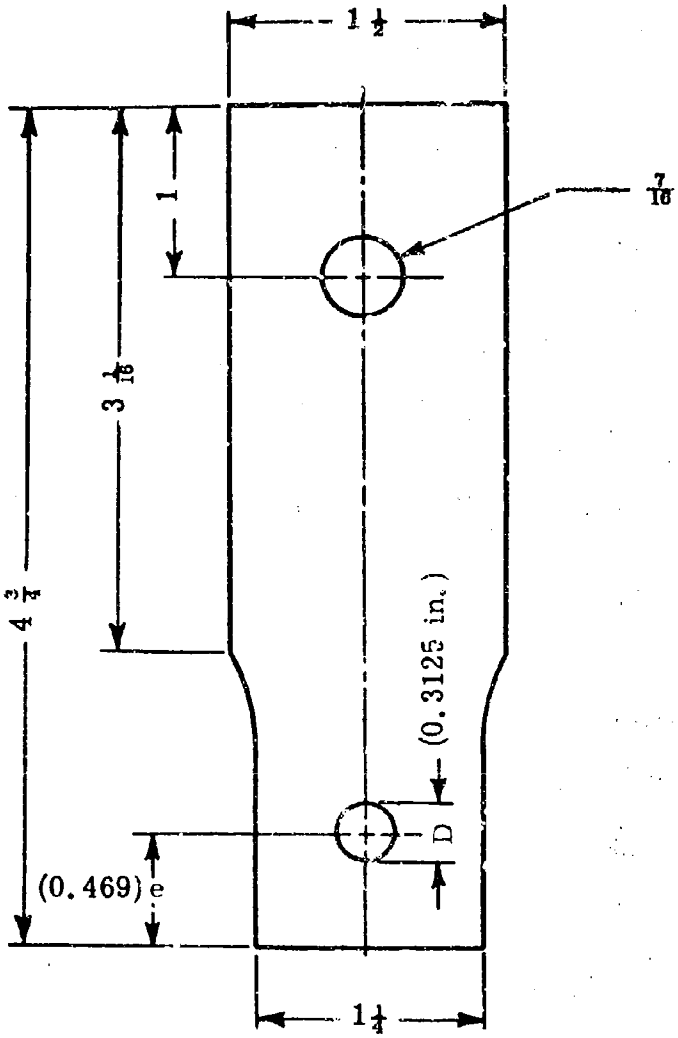
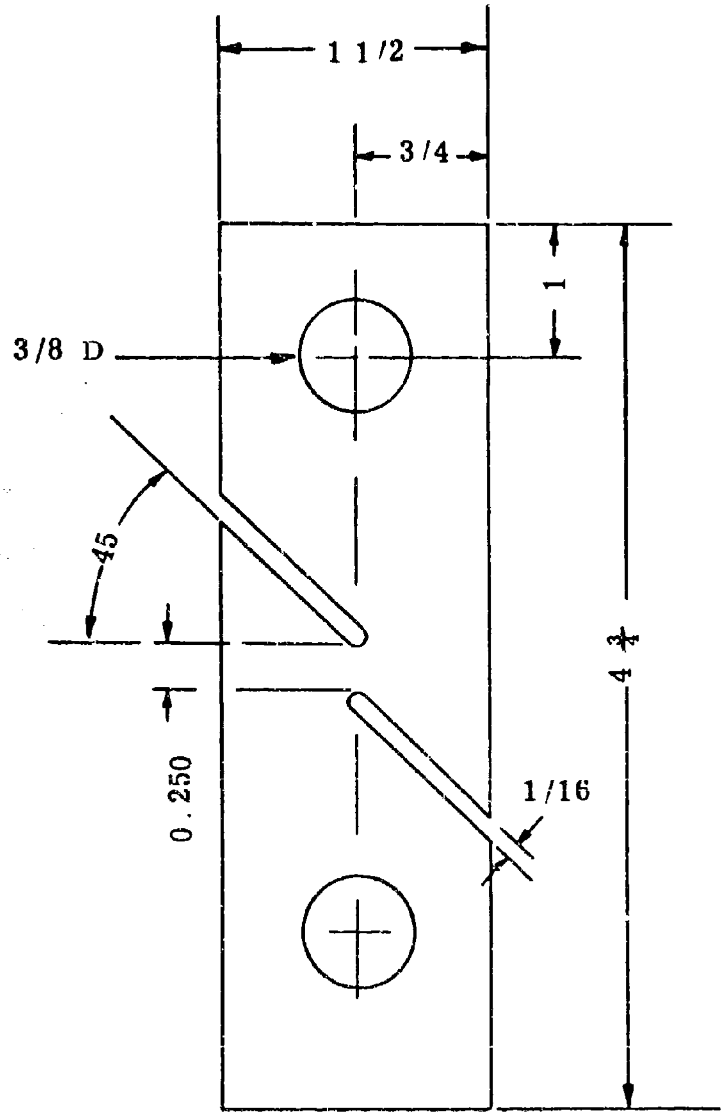


Figure 13. Bearing specimen



a

Figure 14. Shear specimen

W-5%Re vs W-26%Re thermocouple attached to the specimen, which in turn controlled the current to the furnace elements by a saturable reactor. Strain was continuously recorded against time by means of a differential-transformer extensometer, attached to the pull rod of the local train, and a strip-chart recorder. The creep tests were discontinued after 1% deformation so that thermal-stability tests could be performed with the creep-strained specimens.

Thermal Stability

Thermal stability was determined by means of room-temperature tensile evaluations on the tungsten and TZM creep specimens after straining to 1% total creep at selected elevated temperatures. Stress-strain curves were recorded using the equipment described earlier for obtaining room-temperature tensile data. Tensile properties were determined from these curves and are reported along with the tensile elongation and permanent creep elongation.

Weld-Joint Efficiency

The TIG welds of tungsten and TIG and electron-beam (EB) welds of TZM sheet, for evaluation at room temperature and one elevated temperature in the as-welded and welded-and-heat-treated conditions, were accomplished by Westinghouse. The welded materials were subsequently machined into tensile specimens for evaluations to determine the weld-joint efficiency.

Figure 15 shows a typical welded test panel for tungsten or TZM sheet and the location of the tensile specimens in the welded panels. The welding parameters, supplied by Westinghouse, that were followed in the preparation of these panels are given in the summary shown in Table VI.

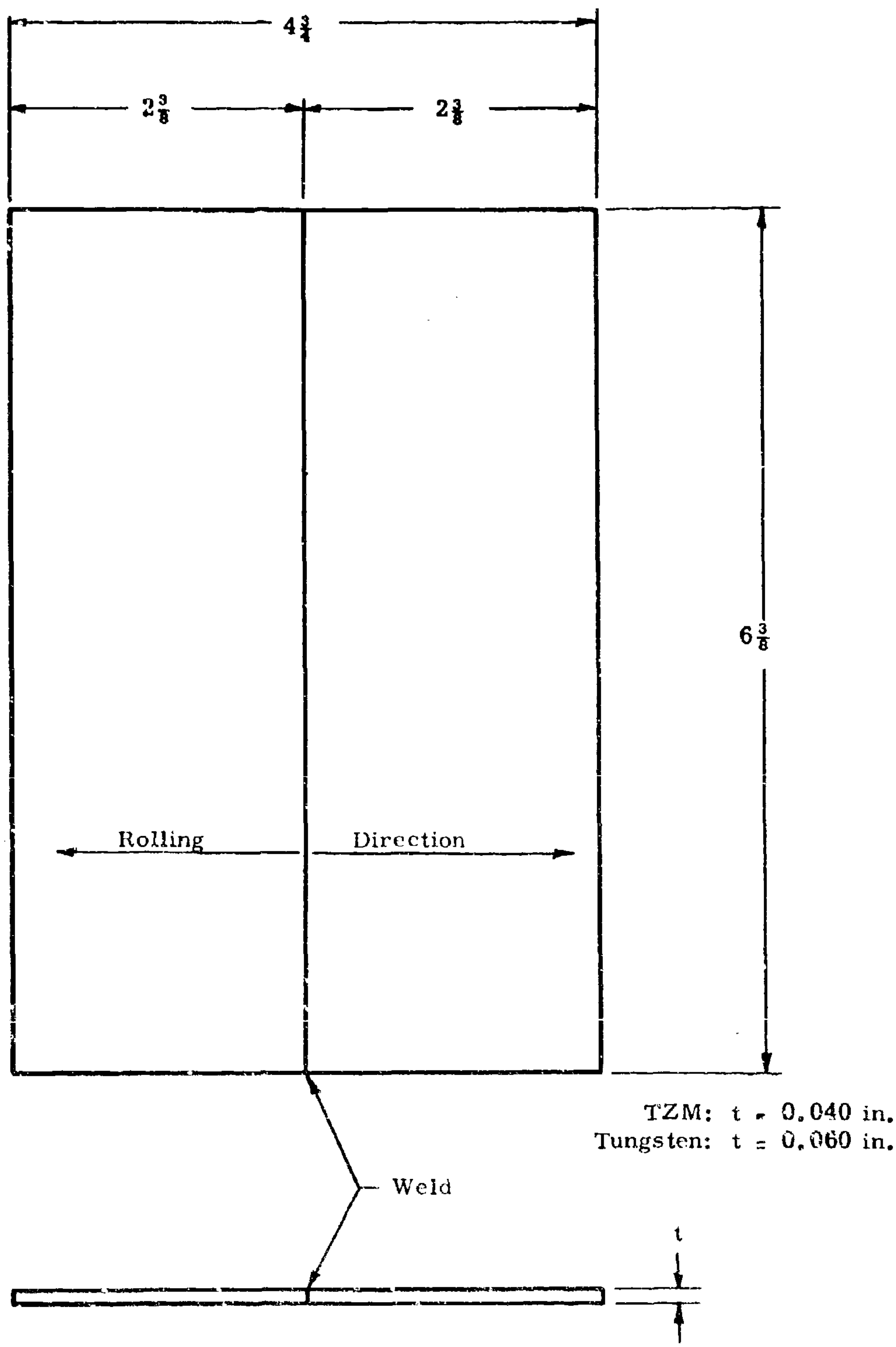


Figure 15. Typical welded test panel from which tensile specimens were machined.

Table VI

Summary of Welding Conditions for Tungsten and TZM Sheet

Material Identity	Preheat °F	Current, Amps	Clamping Space, In.	Weld Speed, IPM	Atmos. Purity ppm O_2	H_2O
TIG Welds on TZM Samples 55-112A to 55-112B	None	100	3/8	7.5	9	3
Samples 56-112A 56-112B	600	95	3/8	7.5	4	3
TIG Welds on Tungsten						
Samples 17A to 17B	600	210	3/8	7.5	6	3
Samples 6A to 6B	600	210	3/8	7.5	7	5
EB Welds on TZM Samples 55-110A to 55-110B	None	5.8	1/2	25	10^{-5} torr	
Samples 56-110A to 56-110B	None	5.8	1/2	25	10^{-5} torr	

All specimens were longitudinally orientated, with the weld perpendicular to the rolling direction of the sheet.

Even though special precautions were used to prevent breakage during preparation, specimens could not be successfully obtained from the welded tungsten panels due to the extreme brittleness of the welds. Because of this, the weld-joint efficiency of the TIG-welded tungsten could not be evaluated. Specimens were successfully machined from the TIG- and EB-welded TZM panels without extraordinary difficulty.

The equipment and procedures used in the tensile tests to determine the weld-joint efficiency were the same as those discussed earlier for room- and elevated-temperature tensile evaluations of the TZM sheet. The strength properties were obtained from the recorded stress-strain curves.

Density

The density of the various sheets of tungsten and TZM alloy was determined by weighing samples in air and in water at 26.3° C (79.3° F). A sample calculation for a tungsten specimen is shown below:

$$\text{Density} = \frac{\text{Weight}}{\text{Volume}} \qquad \begin{array}{ll} \text{Weight} & = \text{Weight in air} \\ \text{Volume} & = \dfrac{\text{Weight in air} - \text{Weight in } H_2O}{\text{Density of } H_2O} \end{array}$$

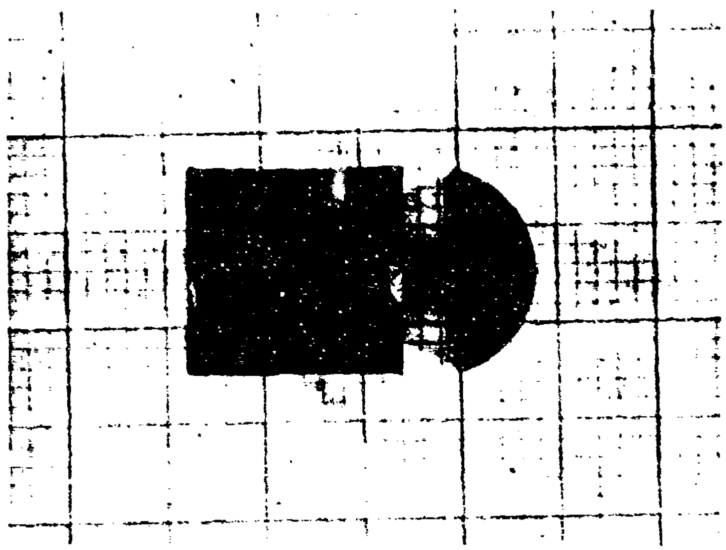
$$\text{Density} = \frac{\text{Weight in air} \times \text{Density of } H_2O}{\text{Weight in air} - \text{Weight in } H_2O} = \frac{32.522 \pm 1 \times 0.99681}{32.522 \quad \pm 1 \quad 30.8360 \pm 2}$$

$$= 19.226 \pm 0.0004 \text{ gms/cc at } 26.3° \text{ C } (79.3° \text{ F})$$

Thermal Conductivity

The specimen configuration used for determination of the thermal conductivity up to 1000° F in the comparative rod apparatus is shown in Figure 16. To make the laminated sheet specimens, squares cut from the sheets were tightly clamped together to form small cubes. Single welds, perpendicular to the sheets, were made at opposite ends of the cubes with an inert-gas arc welder. The specimens were then machined as shown in Figure 16. Most of the weld area was removed in maching and the thermocouple holes were placed outside the heat-affected zones of the welds. A picture of a broken TZM specimen in Figure 16 shows the depth of weld penetration. To prevent oxidation of the samples at the higher temperature, the comparative rod apparatus was partially evacuated several times and purged with helium during the runs. Thermatomic carbon, sifted zirconia, and diatomaceous earth powder were used at different times as insulation for the specimen and reference column. Basically, the determination of thermal conductivity was accomplished by measuring both the heat flux density, flowing axially through the cylindrical specimen, and the temperature gradient along a known axial gage length. The heat flux density was determined with two heat meters or references of known conductivity placed coaxially at the top and bottom of the specimen. The temperature gradient was measured by thermocouples installed in the specimens. Radial losses were carefully controlled with guard heaters. The uncertainty for this equipment is about ± 5%.

In the radial inflow apparatus, which was used to determine thermal conductivity to 2500° F and 3000° F, a cylindrical specimen consisting of stacked discs was radiantly heated, and the radial heat inflow measured by a water calorimeter placed axially through the center of the specimen. Temperature measurements were made at two different radii in the specimens, permitting a



TZM Specimen 1 after exposure. Note weld penetration at each end and path of weld on top surface

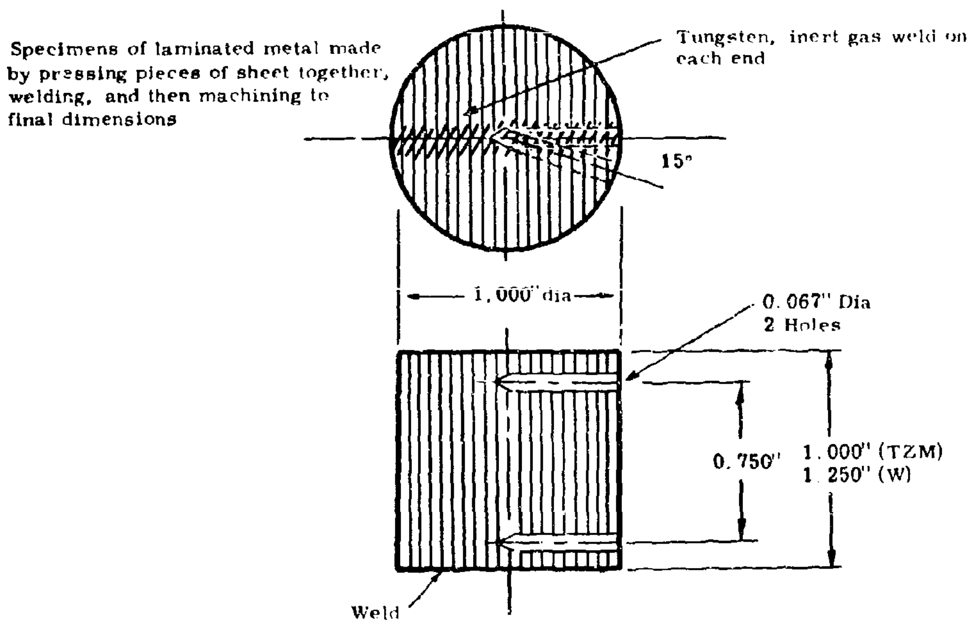


Figure 16. Laminated thermal conductivity specimen configuration for sheet metal materials, and photograph of broken TZM specimen showing depth of heat affected zone.

direct calculation of the conductivity. A helium atmosphere was maintained in this apparatus during the determinations. The probable error for this apparatus has been established at ± 7%. The specimens for this apparatus consisted of from 32 to 34 one-inch di ter discs with one-quarter inch holes in their centers. Temperatures were ..easured at the bottom of small holes drilled axially in the specimen on two different radii, see Figure 17. A one-sixteenth inch diameter tungsten pin was placed through the discs near their outer edge to aid in alignment.

Heat Capacity

For determination of the heat capacity up to 1000° F in the adiabatic calorimeter, the heated (or cooled) specimen, consisting of several small squares of the sheet, was dropped into a thermally guarded c .librated cup, and the specimen enthalpy was measured as a function of the increase in temperature of the cup. In the drop type ice calorimeter, which was used above 1000° F, the heated specimen was dropped into the ice calorimeter, which was surrounded by an ice mantle. The enthalpy of the specimen was determined from measurements of the volume of ice melted as the specimen cooled from its drop temperature to 32° F.

The heat capacities were determined from the slopes of the enthalpy versus temperature curves. Heat capacity was determined graphically and also by using the derivative of an equation for enthalpy obtained using the least squares method. The enthalpy data were first fitted to an equation of the form

$$h_{32} = aT + bT^2 + cT^{-1} + d. \qquad \text{(a)}$$

The derivative of this equation was adjusted to agree with the graphically determined heat capacity at a selected temperature to obtain an equation for heat capacity of the form

$$HC = a + 2bT - c* \ T^{-2} \qquad \text{(b)}$$

Temperatures (T) are in degrees Rankine. Values determined from the equation are generally valid over a range extending from about 100° F from each end point and cannot be used to extrapolate the data.

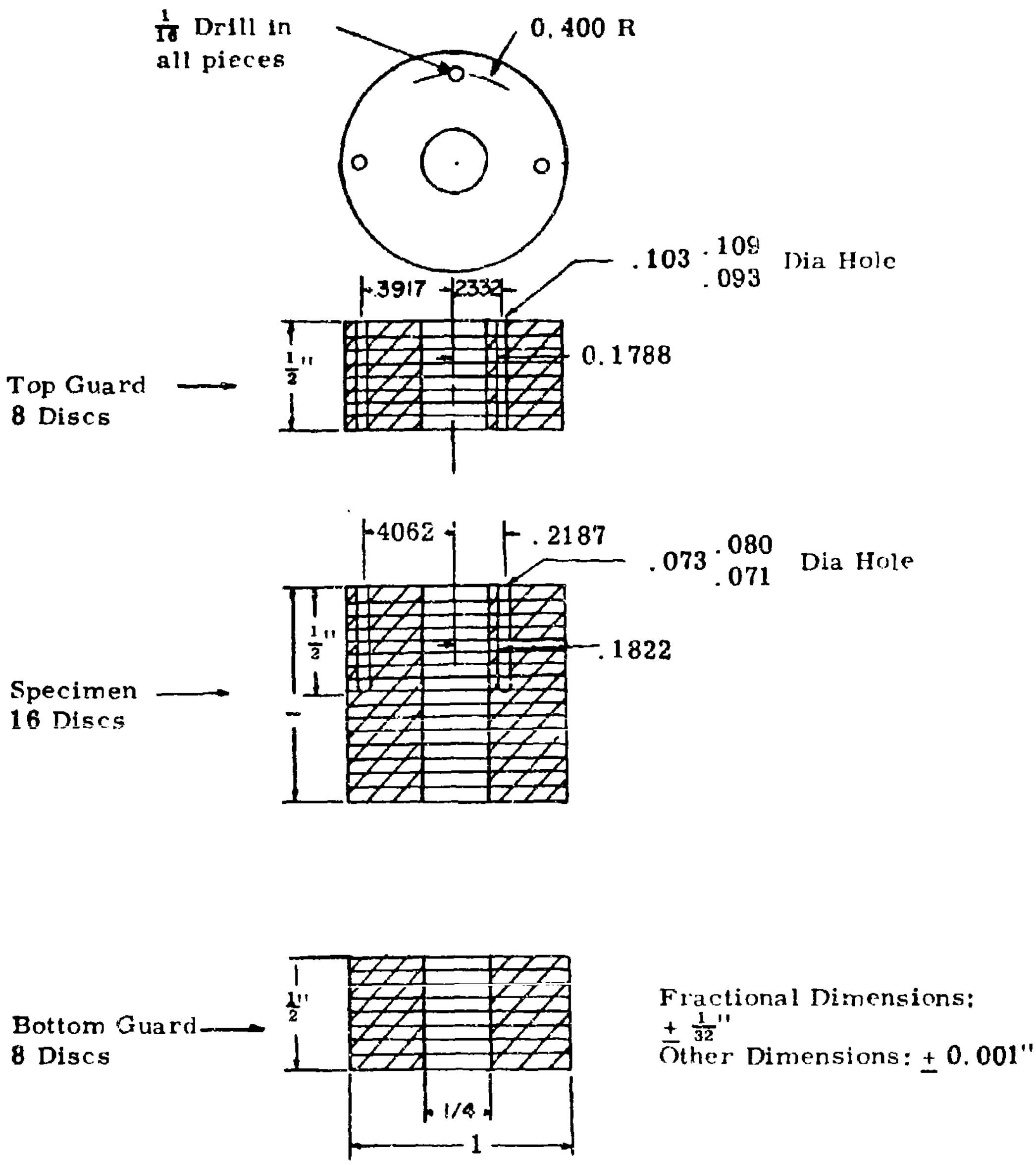


Figure 17. Stacked disc cylindrical thermal conductivity specimen configuration for the radial inflow apparatus.

Thermal Expansion

For determination of thermal expansion, the tungsten specimen was about 3" x 0.50" x 0.10" with each end ground to a 3-inch radius. A graphite sleeve positioned the specimen in the dilatometers. The TZM specimen was made by laminating about six strips of the metal with three welds on each side using an inert gas arc welder. The procedure was similar to that for making the comparative rod conductivity specimens discussed earlier. The laminated specimen was three inches long, about 3/8 inches square, with a three-inch spherical radius on each end. A split graphite sleeve was used to insure good alignment in the dilatometers. All determinations were made in a helium environment. The uncertainty of the thermal expansions determined using the dilatometers has been established at ± 5 percent. Corrections were made for the expansions of the quartz and graphite dilatometers which were reflected in the gage readings. Specimen temperatures below 1000° F in the quartz dilatometer were measured with several thermocouples attached to the specimen. In the graphite dilatometer, a thermocouple near the specimen surface was used to measure specimen temperature from 1000° F to 1500° F. At 1500° F both the thermocouple and an optical pyrometer were used, and above 1500° F optical measurements were used. The thermal expansion data were fitted to an equation similar to equation(a), using the same procedure as used for the heat capacity data. The derivative of this equation was adjusted to agree with the graphically determined coefficient of thermal expansion at a selected temperature to obtain an equation for the coefficient of thermal expansion.

DISCUSSION AND RESULTS

Properties of Tungsten Sheet

Recrystallization Temperature

Materials Advisory Board Specification MAB-192-M defines the recrystallization temperature as the minimum temperature at which in one hour the structure of a material is 50 percent recrystallized and the decrease in hardness is 2/3 of the total decrease from the initial worked condition to the fully recrystallized condition. On this basis, 2400° F was determined as the recrystallization temperature of both the 0.060- and 0.100-in.-thick tungsten sheet.

The R_c and DPH hardness measurements plus estimated percent of recrystallization for the 0.060- and 0.100-in. tungsten sheets are tabulated in Tables VII and VIII and plotted as functions of temperature in Figures 18 through 22. The plots of data for the three 0.060-in. sheets, Figures 18, 19 and 20, show that the decrease in hardness and increase in percentage of recrystallized structure for the sheets are comparable for the same conditions of temperature and time. However, the recrystallized structure of Sheet No. 6 was found to be different from that of Sheets Nos. 15 and 17 as shown in Figure 23. The recrystallized structures of Sheets Nos. 15 and 17 were uniform and had a grain size of about ASTM No. 8, whereas the structure of Sheet No. 6 was irregular and the grain size ranged from ASTM No. 6 to 2, with some subgrains of about ASTM No. 6 visible within the large grains. The structure of Sheet No. 6 in the as-received condition, Figure 1, was coarser than that of Sheets Nos. 15 and 17 and appeared to have had a larger grain size than the other sheets before working.

The recrystallization characteristics of the 0.100-in. tungsten sheet, as shown in Figures 18, 20 and 22 are approximately the same as for the 0.060-in. sheets.

Tensile

The tensile properties from room temperature through 4500° F for the 0.060- and 0.100-in. tungsten sheet in the optimum and recrystallized conditions are summarized in Tables IX through XII and plotted in Figures 24 through 28. In addition to data obtained at the scheduled evaluation temperatures, these figures also show results from unnotched specimens that were tested to define the notched-unnotched strength ratio, which will be discussed subsequently.

Table VII

The Hardness and Percent Recrystallization of Three 0.060 In. Thick Tungsten Sheets[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. °F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
Sheet No. 15					
C-15	As-Received		42.8	443	-
A-15	5	1800	42.8	-	-
B-15	5	2000	43.1	-	-
D-15	5	2200	42.7	-	-
E-15	5	2400	42.6	440	1
U-15	5	2425	43.8	-	-
P-15	5	2500	42.4	438	10
V-15	5	2525	41.1	427	15
S-15	5	2550	39.7	413	30
X-15	5	2575	37.5	388	75
F-15	5	2600	36.7	372	90
G-15	5	2800	35.6	362	100
H-15	5	3000	34.6	359	-
I-15	60	1800	44.4	458	-
J-15	60	2000	43.7	443	-
K-15	60	2200	42.6	439	2
L-15	60	2400	41.6	422	40
T-15	60	2425	38.6	389	80
R-15	60	2450	36.1	367	100
Q-15	60	2500	36.3	364	-
M-15	60	2600	36.1	-	-
N-15	60	2800	36.1	363	-
O-15	60	3000	35.3	-	-
Sheet No. 17					
G-17	As-Received		43.4	-	-
A-17	5	2500	44.7	439	8
B-17	5	2575	41.6	362	75

Table VII (Continued)

The Hardness and Percent Recrystallization of Three 0.060 In. Thick Tungsten Sheets[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. °F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
Sheet No. 17 (Continued)					
C-17	60	2200	43.4	438	3
D-17	60	2400	36.9	463	77
E-17	60	2425	38.1	356	90
F-17	60	2700	36.5	352	100
Sheet No. 6					
G-6	As-Received		42.7	-	-
A-6	5	2500	41.6	434	10
B-6	5	2575	39.6	414	60
C-6	60	2200	42.3	437.	3
D-6	60	2400	38.7	373.	60
E-6	60	2425	40.6	361.	65
F-6	60	2700	32.7	350	100

[1] Sheet numbers 6, 15, and 17 from Fansteel Lot No. A5467. Specimen number suffix denotes sheet number.

[2] Specimens in optimum condition were resistance heated in a vacuum of 1×10^{-5} torr.

[3] Rc hardness measured on surface of the sheet.

[4] DPH at mid-thickness on a longitudinal section with a 3 Kg load.

Table VIII

The Hardness and Percent Recrystallization of 0.100 In. Thick Tungsten Sheet[1] After Holding at Different Temperatures for Five and Sixty Minutes[2]

Specimen No.	Time at Temp. Min.	Temp. °F	Rc Hardness[3]	DPH[4]	Estimated Recrystallization %
K	As-Received		41.7	438	1
B	5	1800	43.9	485	1
C	5	2000	43.9	466	1
D	5	2200	43.8	462	1
Y	5	2300	42.0	-	-
E	5	2400	41.8	458	5
L	5	2500	40.2	433	20
F	5	2600	37.4	378	95
Z	5	2700	35.0	361	100
G	5	2800	35.0	359	-
N	5	2900	33.7	-	-
H	5	3000	33.8	-	-
I	5	3200	33.6	359	-
O	60	1900	41.9	449	5
P	60	2100	41.0	445	5
Q	60	2300	40.9	441	10
U	60	2400	38.3	388	60
R	60	2500	34.6	347	100
V	60	2600	34.3	344	-
S	60	2700	33.7	346	-
W	60	2800	33.2	346	-
T	60	2900	33.6	349	-
X	60	3000	33.0	344	-

[1] Sheet No. 112 from Fansteel Lot No. A 5467.

[2] Specimens in optimum condition were resistance heated in a vacuum of 1×10^{-5} torr.

[3] Rc hardness measured on surface of the sheet.

[4] DPH at mid-thickness on a longitudinal section with a 3 Kg load.

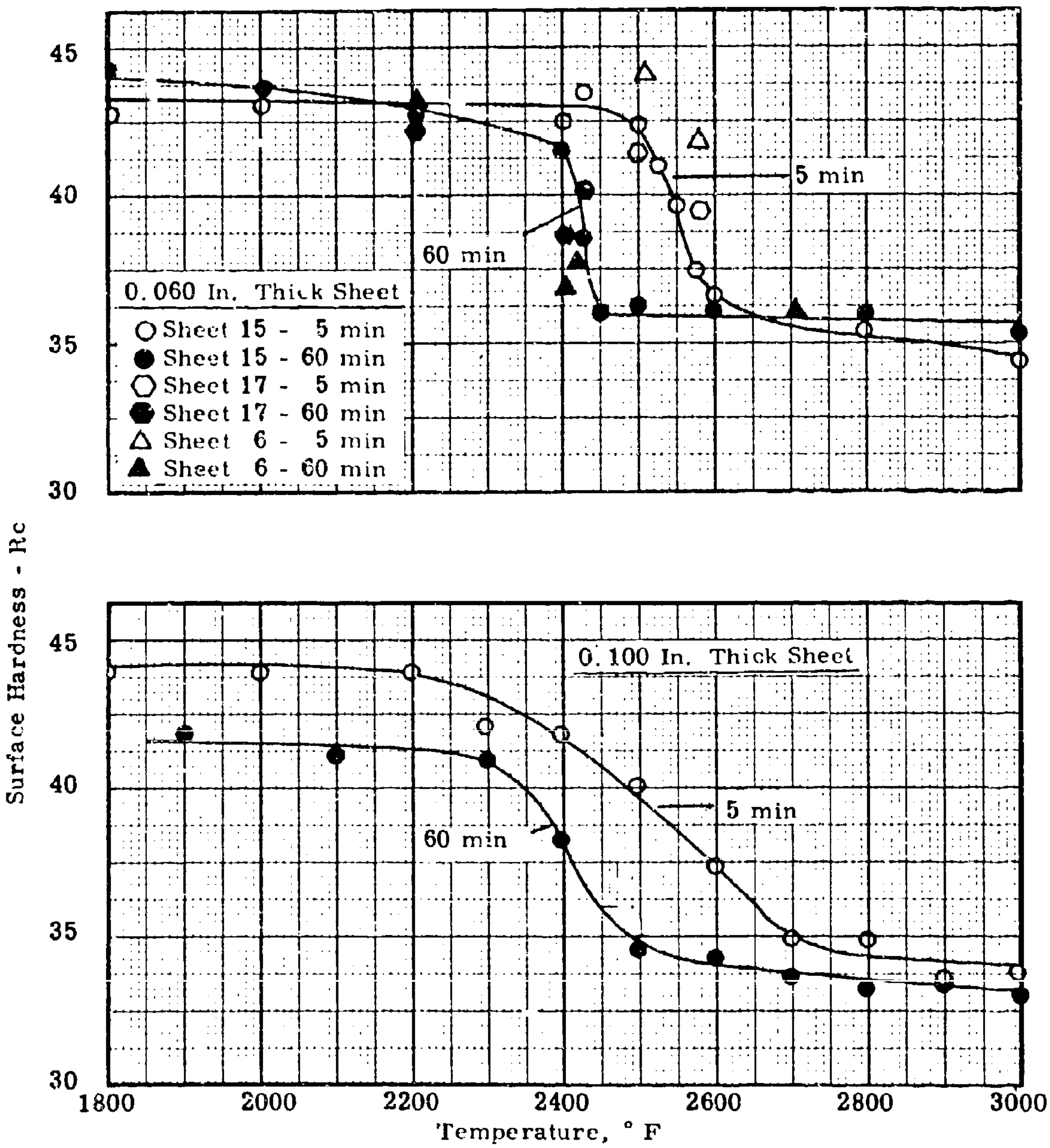


Figure 18. The Rc hardness of 0.060-and 0.100-in.-thick tungsten sheet after holding 5 and 60 min at different temperatures.

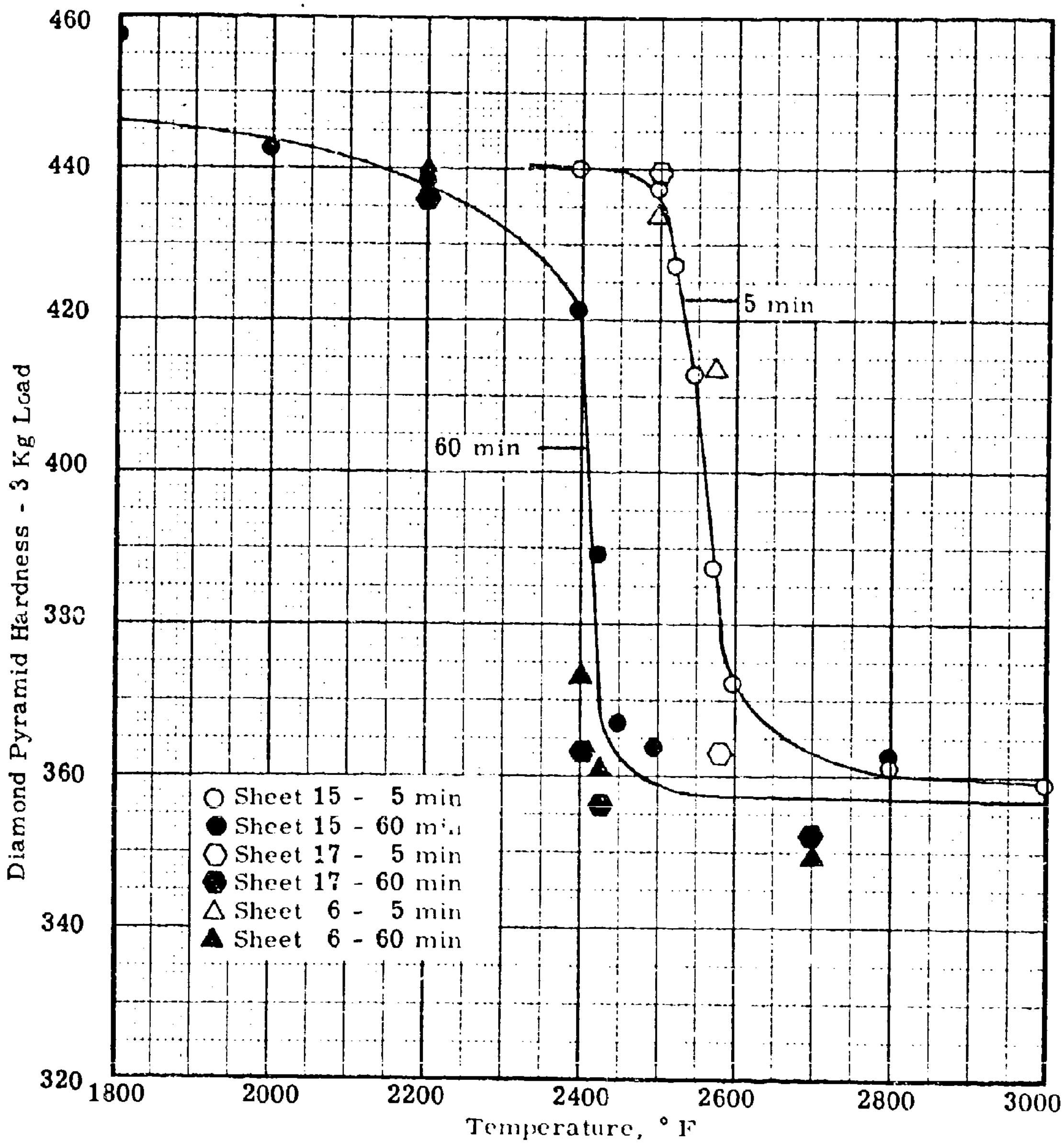


Figure 19. The DPH at the mid-thickness on longitudinal sections of different 0.060-in.-thick tungsten sheet after holding 5 and 60 min at different temperatures.

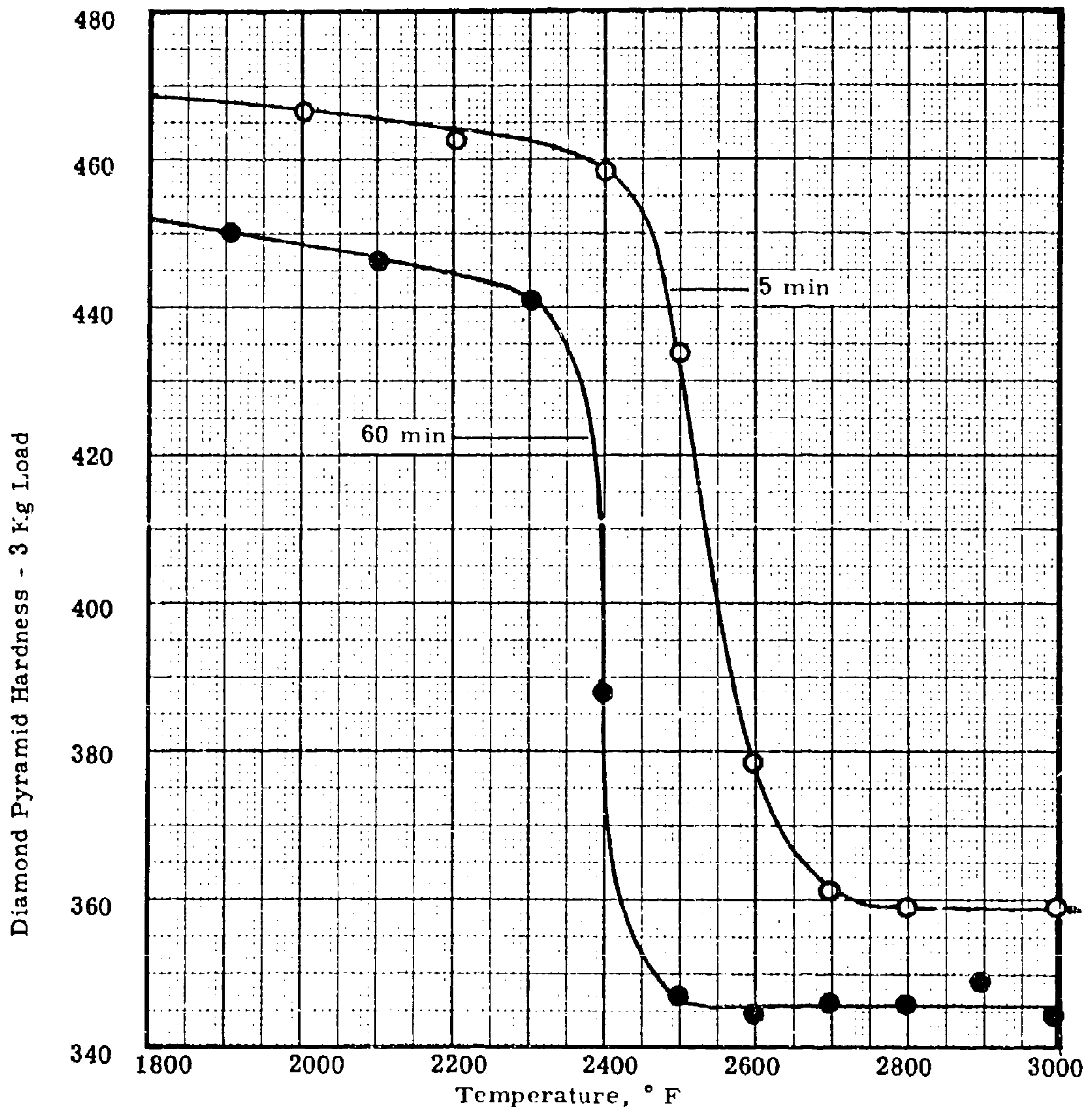


Figure 20. The DPH at mid-thickness on longitudinal sections of 0. 100-in.-thick tungsten sheet after holding 5 and 60 min at different temperatures.

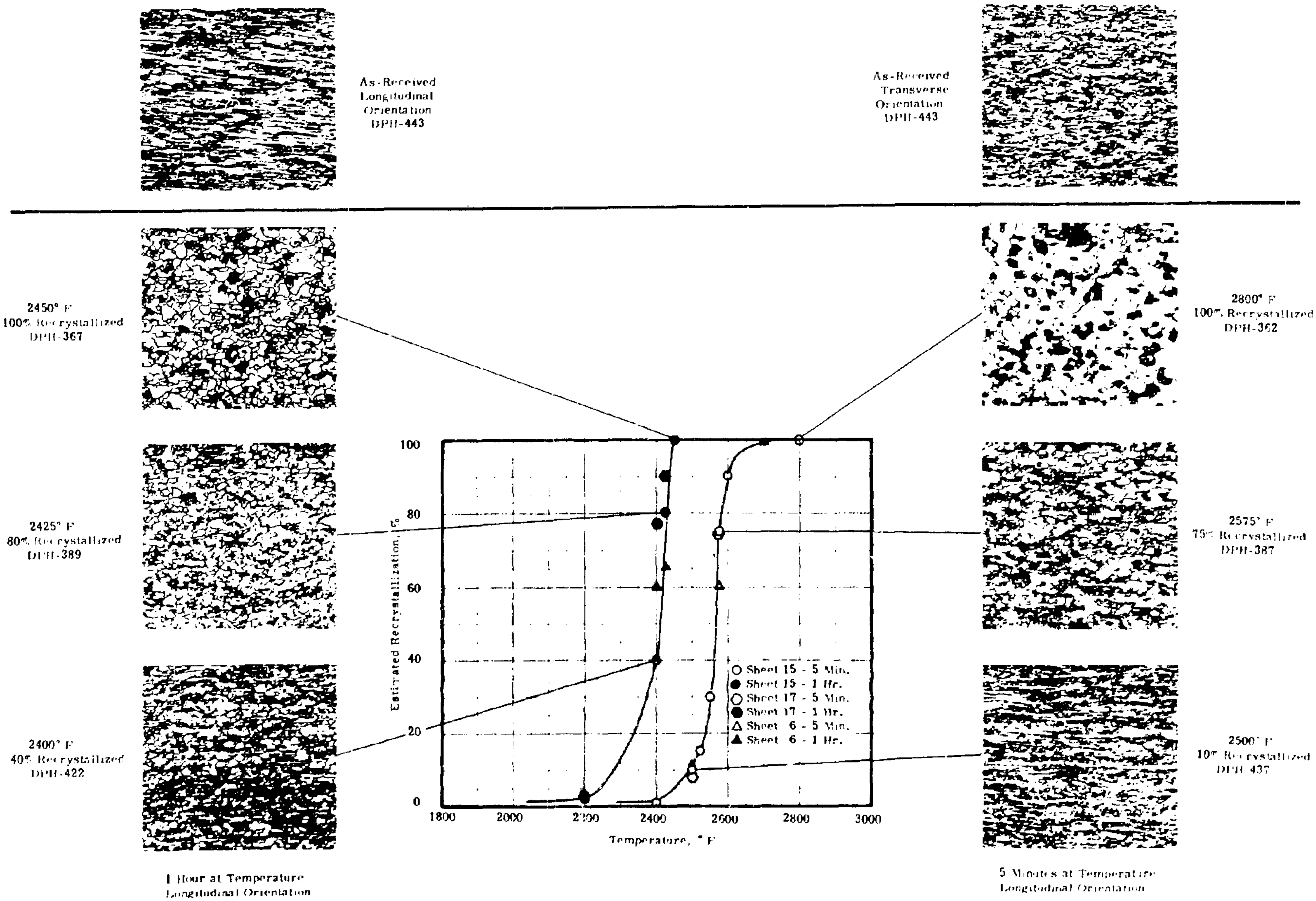


Figure 21. Effect of temperature and time at temperature on the recrystallization of 0.060-in.-thick tungsten sheet.
Photomicrographs: Magnification 100X; Etchant - $K_3Fe(CN)_6$.

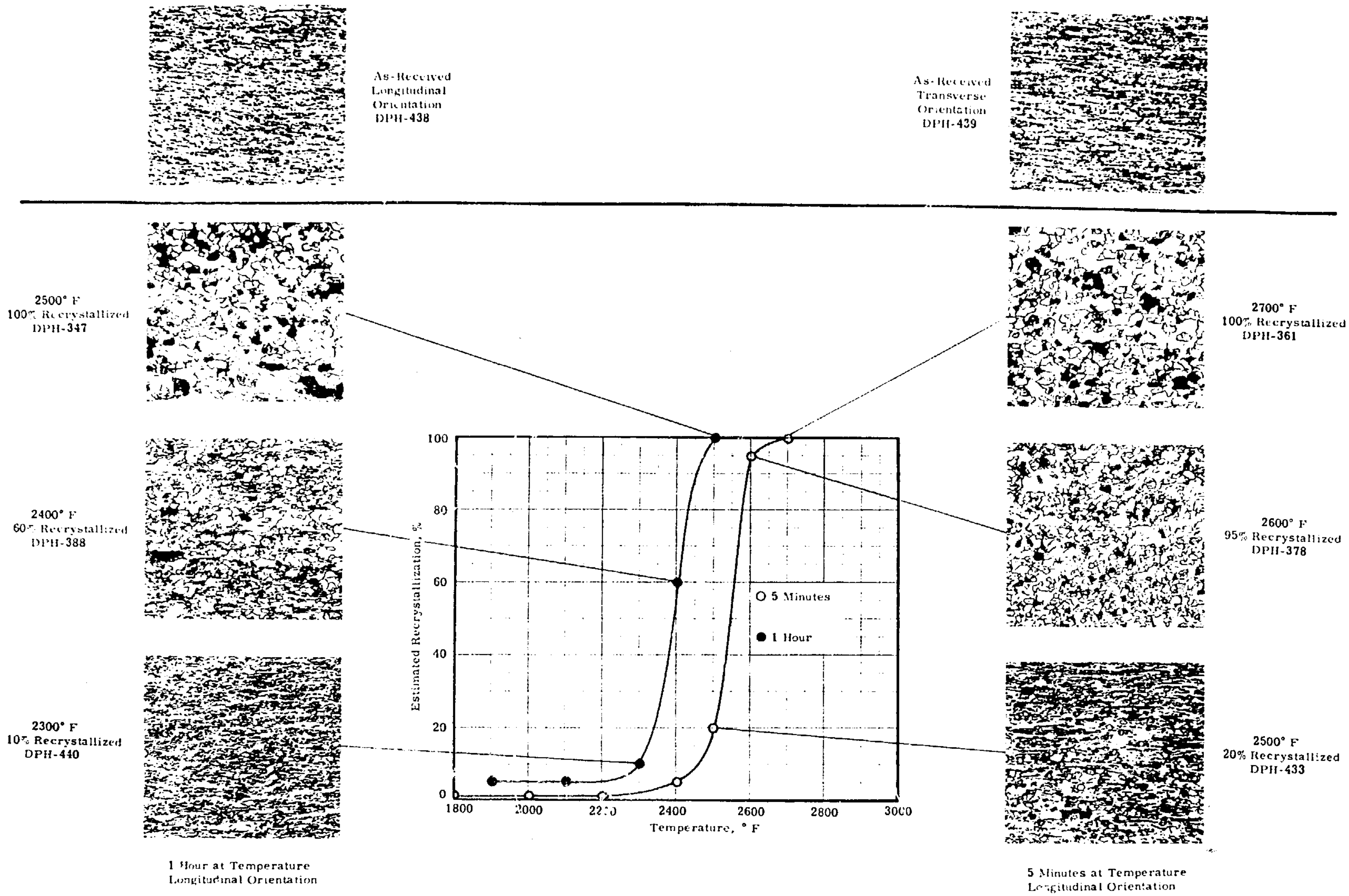
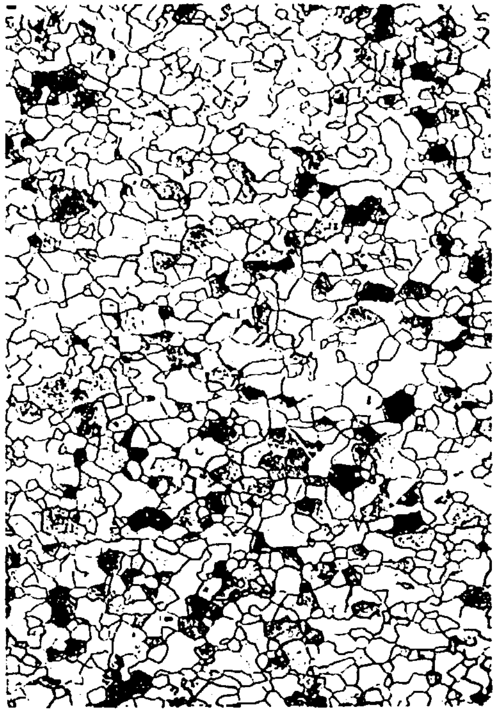


Figure 22. Effect of temperature and time at temperature on the recrystallization of 0.100-in.-thick tungsten sheet. Photomicrograph: Magnification 100X; Etchant - $K_3Fe(CN)_6$.

Sheet No. 6



Sheet No. 15

Sheet No. 17

Figure 23. Comparison of the longitudinal microstructure of the three 0.060-in.-thick tungsten sheets after recyrstallization at 2700° F for 60 min. Magnification: 100X Etchant: $K_3Fe(CN)_6$

Table IX

Tensile Properties of 0.060-In.-Thick Tungsten Sheet in the Optimum Condition at Different Temperatures[1]

Specimen No.	Orientation	Temp., °F	0.2%-Offset Yld. Str., ksi	Ultimate Ten. Str., ksi	Mod. of Elasticity, 10^6 psi	Elong. in 1.25 in., %	Reduction of Area, %
6-150	Long.	70	188.0	190.5	46	0.5	–[2]
17-295	Long.	70	200.0	208.0	48	0.8	–[2]
15-2	Long.	70	196.0	200.5	56	0.8	–[2]
Average			194.7	199.7	50	0.7	
15-136	Trans.	70	216.1	218.5	52	0.5	–[2]
17-438	Trans.	70	–[3]	150.0[3]	52	0	–[2]
Average			216.1	218.5	52	0.2	
15-4	Long.	1200	77.4	87.2	43	7	61
6-141	Long.	1200	77.0	82.2	42	7	51
Average			77.2	84.7	43	7	56
17-284	Long.	2000	62.7	66.0	38	8	68
6-142	Long.	2000	59.0	62.2	43	8	70
Average			60.8	64.3	41	8	69
5-15	Long.	2500	45.7	54.9	48	9	>95
17-285	Long.	2500	48.6	57.1	35	10	>95
Average			47.6	56.0	42	10	>95
6-15	Long.	3000	7.6	17.4	44	60	>95
6-143	Long.	3000	6.7	18.7	42	71	>95
Average			7.1	18.0	43	64	>95
6-144	Long.	3500	5.8	12.6	43	59	69
17-286	Long.	3500	6.5	13.2	33	50	70
Average			6.1	12.9	38	54	70
17-287	Long	4000	–[4]	6.7	17	24	60
15-7	Long	4000	4.0	7.5	15	22	69
Average			4.0	7.1	16	23	64
15-8	Long	4500	1.4	2.3	12	21	59
6-145	Long	4500	2.0	3.1	11	10	32
Average			1.7	2.7	11	16	45

[1] Specimens were heated by radiation in a vacuum of approximately 1×10^{-4} torr and held at temperature 15 min before straining. At 70 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above, the strain rate was 0.05 min^{-1} to fracture.

[2] Too small to be measured.

[3] Specimen fractured before 0.2% offset.

[4] Extensometer slipped before 0.2% offset.

Table X

Tensile Properties of 0.060-In.-Tungsten Sheet in the Recrystallized Condition at Different Temperatures[1,2]

Specimen Number	Orien-tation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Tens. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
15-12	Long	75	-[3]	56.8	56	0	0
17-294	Long	75	-[3]	55.8	68	0	0
Average				56.3	62	0	0
15-137	Trans	75	-[3]	47.8	68	0	0
17-439	Trans	75	-[3]	67.7	64	0	0
6-269	Trans	75	-	44.3	66	0	0
Average				53.3	66	0	0
6-156	Long	1200	11.1	44.1	47	53	74
6-151	Long	1200	9.0	41.0	47	52	75
17-296	Long	1200	13.8	55.0	34	55	72
Average			11.3	46.7	43	53	74
15-13	Long	2000	10.0	34.4	52	31	>95
17-297	Long	2000	12.1	40.0	40	47	>95
Average			11.0	37.2	46	39	>95
6-152	Long	2500	7.3	27.5	38	51	>95
17-298	Long	2500	8.6	26.7	43	52	>95
Average			8.0	27.1	41	52	>95
6-153	Long	3000	8.6	19.3	44	71	86
15-14	Long	3000	8.0	18.7	42	44	>95
Average			8.3	19.0	43	58	>90
15-15	Long	3500	6.1	11.8	45	50	60
17-299	Long	3500	5.8	11.1	31	48	50
Average			6.0	11.5	38	49	55
17-300	Long	4000	4.3	8.4	16	24	59
17-301	Long	4000	4.7	9.0	16	23	64
Average			4.5	8.7	16	24	62
6-154	Long	4500	2.0	4.5	10	18	54
6-155	Long	4500	2.3	4.3	9	17	46
Average			2.2	4.4	10	18	50

[1] Specimens were recrystallized at 2550° F in 1 hour.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Specimen fractured before yielding.

Table XI

Tensile Properties of 0.100-In.-Thick Tungsten Sheet in the Optimum Condition at Different Temperatures[1]

Specimen No.	Orientation	Temp. °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Elasticity 10^6 psi	Elong. in 1.25 in. %	Reduction of Area %
112-8	Long	70	192.3	196.5	40	0.5	-[2]
112-9	Long	70	193.0	199.0	46	0.7	-[2]
Average			192.6	197.8	43	0.6	
112-30	Trans	70	212.0	215.2	53	0.5	-[2]
112-31	Trans	70	212.5	217.0	49	0.6	-[2]
Average			212.2	215.2	51	0.6	
112-10	Long	2000	63.2	68.2	29	11	84
112-11	Long	2000	63.2	67.2	35	11	86
Average			63.2	67.7	32	11	85
112-12	Long	2500	[illegible].2	54.0	31	12	>95
112-13	Long	2500	45.5	55.0	32	11	>95
Average			44.4	54.5	32	12	>95
112-14	Long	3000	7.4	16.5	33	70	>95
112-115	Long	3000	7.4	17.9	32	83	>95
Average			7.4	17.2	32	77	>95
112-16	Long	3500	5.7	12.8	31	69	67
112-17	Long	3500	5.6	12.0	38	70	69
Average			5.6	12.4	35	70	68
112-18	Long	4000	4.3	8.2	25	32	>95
112-19	Long	4000	5.4	7.6	19	24	>95
Average			4.9	7.9	22	28	>95
112-20	Long	4500	4.4	6.0	7	22	56

[1]Specimens were heated by radiation in a vacuum of approximately 1×10^{-4} torr, held 15 min at temperature, and strained at 0.05 min^{-1} to fracture at 2000°F and above. At room temperature specimens were strained at 0.005 min^{-1} to 0.6% offset and at 0.05 min from 0.6% offset to fracture.

[2]Too small to be measured.

Table XII

Tensile Properties of 0.100-In.-Thick Tungsten Sheet in the Recrystallized Condition at Different Temperatures[1,2]

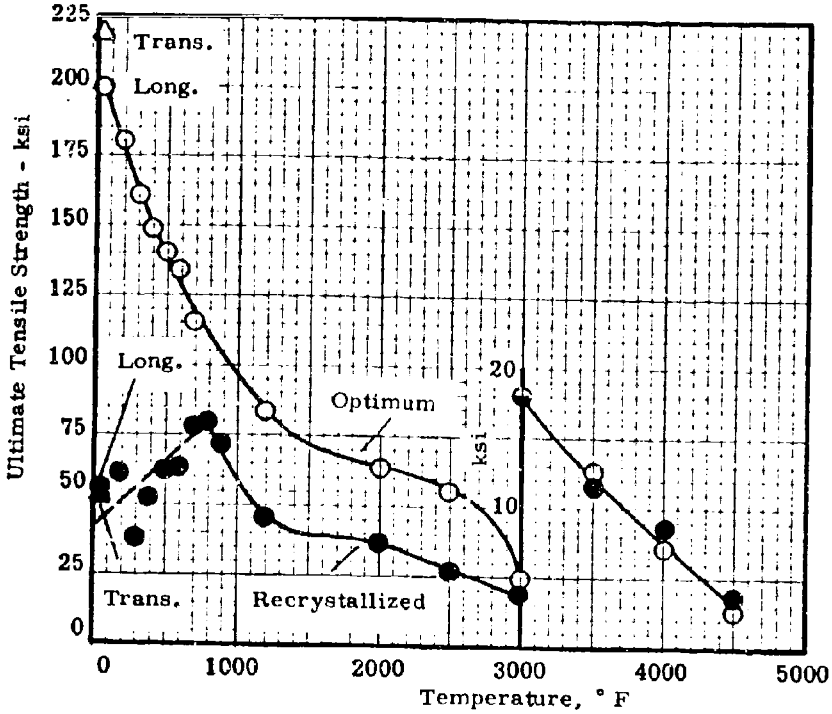
Specimen Number	Orien-tation	Temp, °F	0.2%-Offset Yld. Str., ksi	Ultimate Ten. Str., ksi	Mod. of Elasticity, 10^6 psi	Elong. in 1 in., %	Reduction of Area, %
112-22	Long	75	-[3]	>77.0[4]	59	0	0
112-23	Long	75	-[3]	>52.6[4]	70	0	0
Average			-	>64.8	65	0	0
112-32	Trans	75	-[3]	>46.4[4]	61	0	0
112-33	Trans	75	-[3]	>59.2[4]	71	0	0
Average			-	>52.8	66	0	0
112-24	Long	2500	6.8	29.2	41	50	>95
112-25	Long	2500	8.7	30.4	49	53	>95
Average			7.8	29.8	45	52	>95
112-28	Long	3000	6.6	18.6	41	57	>95
112-29	Long	3000	5.8	18.0	36	56	>95
Average			6.2	18.3	38	56	>95

1 Specimens were recrystallized at 2550° F in 1 hour.

2 Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

3 Specimen fractured before yielding.

4 Specimen broke at radius of shoulder.



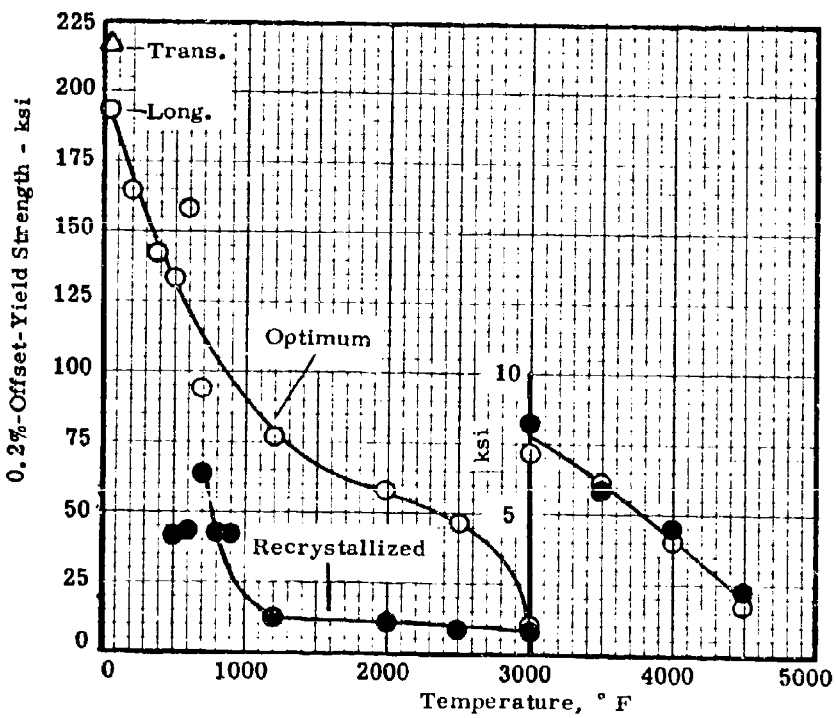
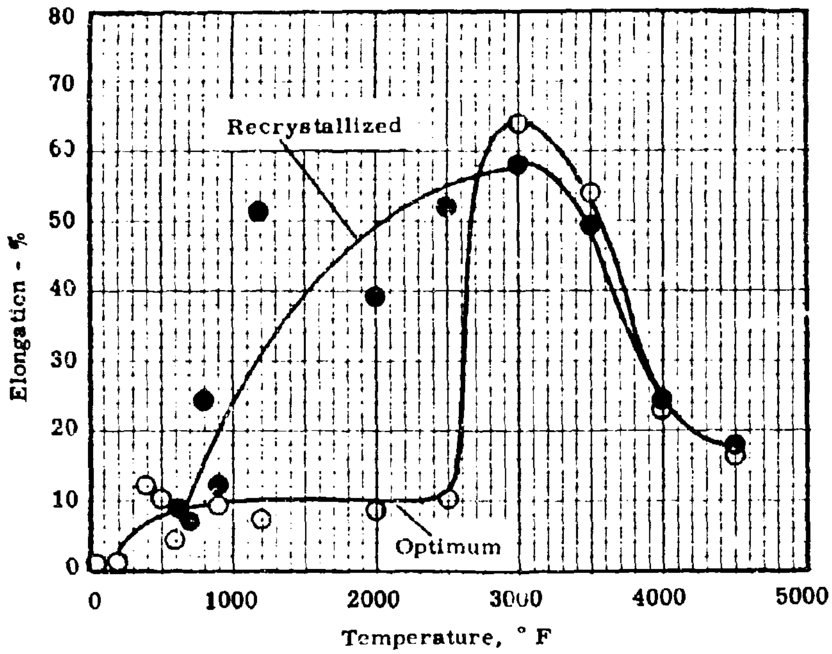


Figure 24. The ultimate-tensile and 0.2%-offset-yield strengths at different temperatures of 0.060-in. tungsten sheet in the optimum and recrystallized conditions.



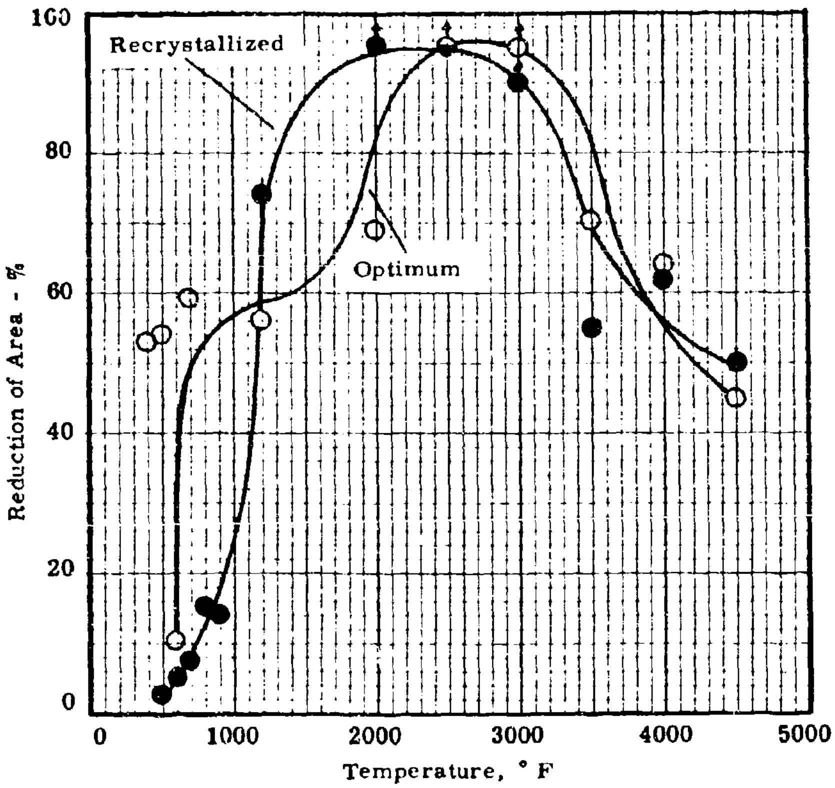
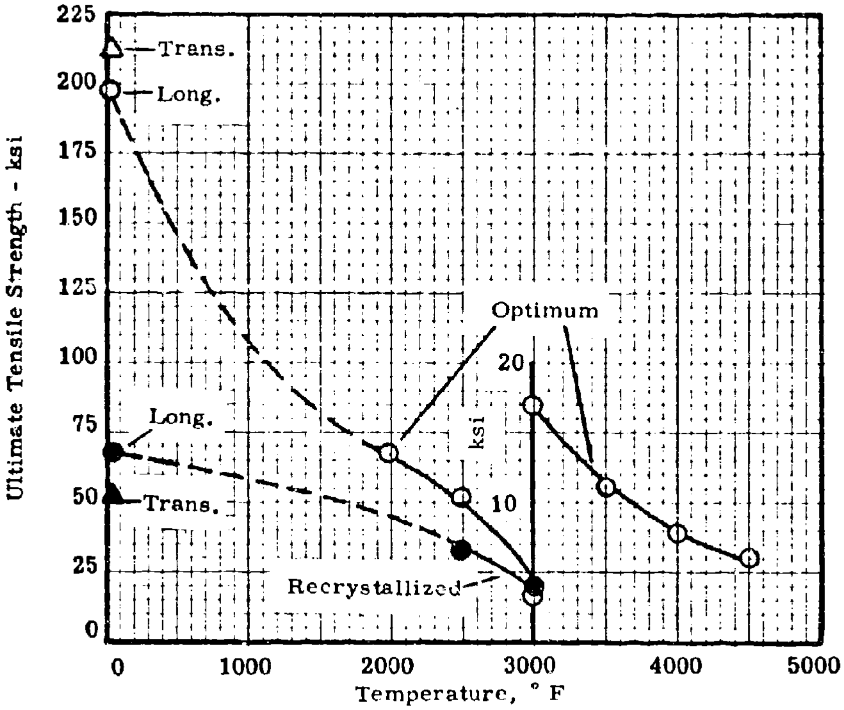


Figure 25. The elongation and reduction of area of 0.060-in. tungsten sheet in the optimum and recrystallized conditions at different temperatures.



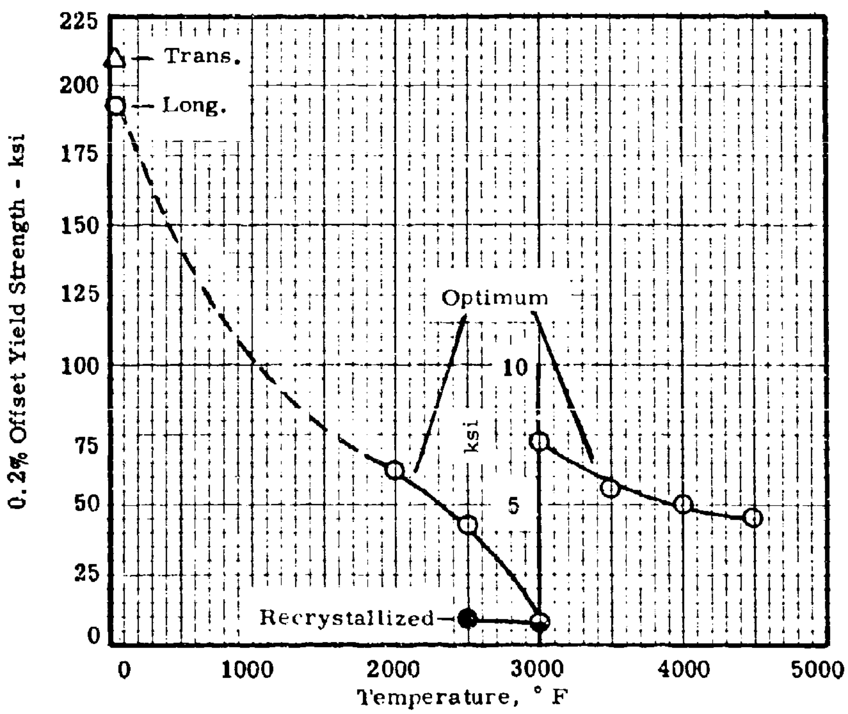


Figure 26. The ultimate-tensile and 0.2%-offset-yield strengths at different temperatures of 0.100 in. tungsten sheet in the optimum and recrystallized conditions.

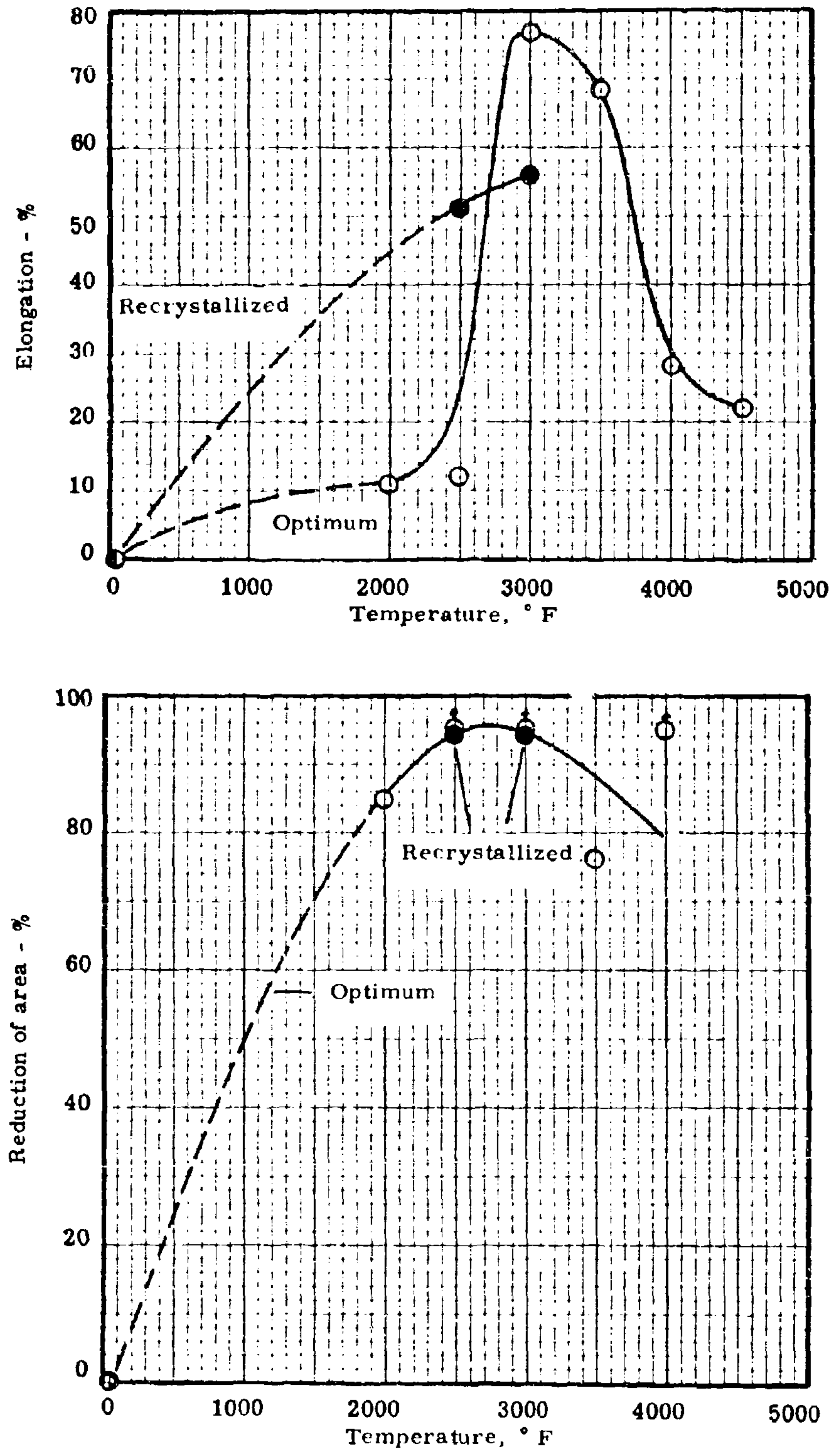


Figure 27. The elongation and reduction of area of 0.100-in. tungsten sheet in the optimum and recrystallized conditions at different temperatures.

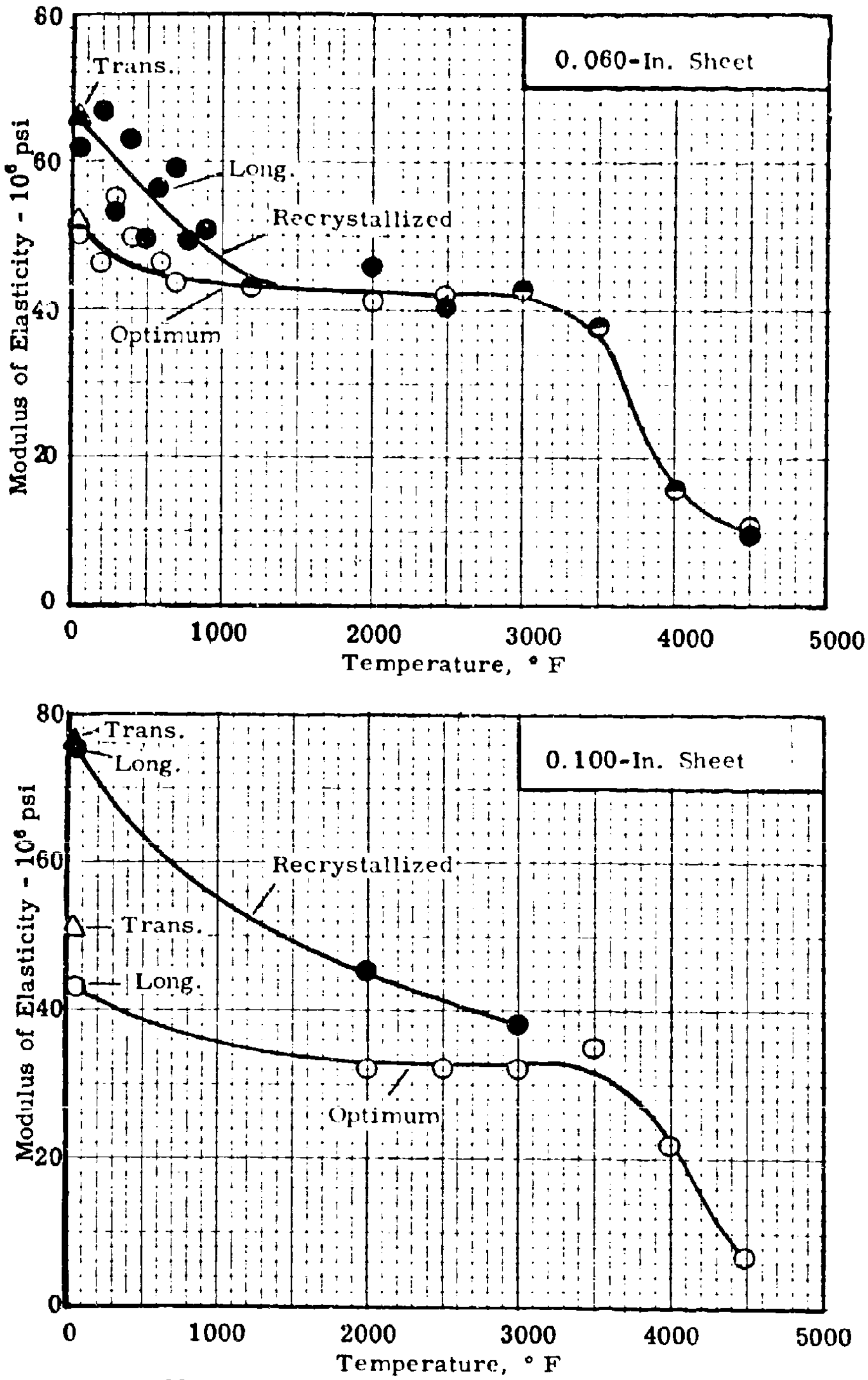


Figure 28. The modulus of elasticity at different temperatures of 0.060-in. and 0.100-in. tungsten sheet in the optimum and recrystallized conditions.

The room-temperature tensile properties were comparable for both gages of the tungsten sheet in the optimum condition. The tensile strength properties were, however, about 3 to 5 ksi higher for the transverse direction than they were for the longitudinal direction. As shown in Figures 24 and 26, for the 0.060-in. and 0.100-in. sheet respectively, the strength properties of the recrystallized sheet were much lower than those of the optimum sheet. Brittle fracture of the recrystallized sheet limited the tensile strength at room temperature to lower values than were obtained at moderately elevated temperatures (up to 1000° F). There was not a significant difference in the tensile strengths of the recrystallized sheet in the longitudinal and transverse directions.

As the testing temperature was increased from room temperature to about 1000° F, the strength of the tungsten sheet in the optimum condition (warm worked and stress relieved) decreased from about 200 ksi to about 100 ksi, as may be seen in Figures 24 and 26, with a corresponding decrease in yield strength. This rapid decrease in strength with a rather slight increase in temperature is normal for tungsten and some other body-centered cubic metals such as molybdenum. The decrease in strength between 1000 and 2500° F was gradual, about 25 psi $°F^{-1}$. A large decrease in strength occurred between 2500 and 3000° F, which is attributable to recrystallization. Above the recrystallization temperature the strength decreased as a linear function of the testing temperature to about 15 ksi at 4500° F.

The yield and tensile strength of the recrystallized tungsten sheet was lower than for the sheet in the optimum condition at all temperatures up to the recrystallization temperature. Above the recrystallization temperature the properties of the originally optimum-condition sheet, which recrystallized during testing, and the previously recrystallized sheet were comparable.

At room temperature the elongation of the optimum-condition sheet was less than one percent and the reduction in area was too small to be measured. At room temperature and up to about 700° F the recrystallized structure fractured in a brittle manner, consequently the elongation and reduction in area were zero. As Figures 25 and 27 show, the elongation of the sheet in the optimum condition was between 5 and 10% at 1000° F up to 2500° F, slightly below the recrystallization temperature. Over this same temperature range the elongation of the recrystallized sheet was significantly higher at 40 to 55%. At 3000° F and higher, at which temperatures the "optimum-condition" sheet was recrystallized during testing, both sheet materials had practically the same elongation at comparable testing temperatures. The elongation decreased from its maximum value of about 60% at 3000° F to about 16% at 4500° F. The reduction in area for both heat-treated conditions was similar over the entire testing temperature range. That is, the reduction in area increased sharply from less than about 20% at 1000° F to greater than 95% from 2000 through 3000° F, above which it decreased to about 50% at 4500° F.

Figure 28 shows the modulus of elasticity for both thicknesses of the tungsten sheet in the optimum and recrystallized conditions as functions of the testing temperature. At room temperature, the modulus of elasticity of the sheet in the optimum condition was about 10 million psi lower than in the recrystallized condition for both the 0.060-in. and 0.100-in. thicknesses. Generally, the elastic modulus was slightly higher in the transverse direction than in the longitudinal direction at room temperature. As the testing temperature was increased, the modulus of elasticity of the recrystallized sheet converged with that for the optimum-condition sheet at about 1000° F. At higher temperatures the moduli of elasticity for both heat treated conditions were generally comparable. Between 1000° F and about 3000° F, the modulus of elasticity was about 40×10^6 psi for all the tungsten sheet tested in this temperature range. Between 3000 and 4000° F, the modulus of elasticity decreased from about 40×10^6 psi to about 10×10^6 psi.

Although each of the three tungsten sheets was not tested at each temperature, the results of single tests from two different sheets at each temperature did not show a significant or consistent difference in the tensile properties among the three 0.060-in. sheets that were samples in the program.

Notch-Tensile Properties

Tables XIII and XIV summarize, for the 0.060-in. tungsten sheet in the optimum and recrystallized conditions respectively, data from notched and unnotched tensile specimens that were evaluated to determine the brittle-ductile transition temperature. Most of the data for the unnotched condition were obtained from specimens that were finished by machine grinding. However, because most of the unnotched specimens that were evaluated at 400° F and below fractured in the radius or across the shoulders through the pin holes, a few specimens in the optimum condition were electropolished in an attempt to reduce this abnormal tendency. Electropolishing was accomplished in a two-percent solution of NaOH in water. Approximately 0.002 in. was removed from the ground-edge surfaces and the rolled surfaces of the sheet by electropolishing.

The range of the ductile-brittle transition temperature for the tungsten in both conditions was determined from the data plotted in Figures 29 and 30 as shown in Table XV.

Table XIII

Notched-Tensile and Unnotched-Tensile Data for 0.060-In. Tungsten Sheet in the Optimum Condition[1] at Moderately-Elevated Temperatures[2]

Temp °F	Unnotched Specimens: Specimen No.	0.2% Offset Yld. Str. ksi	Ultimate Tens. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Red. of Area %	Notched Specimens: Specimen No.	Ultimate Tens. Str. ksi	Notched/Unnotched Strength Ratio
200	6-146[4]	164.0	172.0	48.1	0.6	0	306	95.0	
200	15-9	–[3]	188.0	44.2	0	0	15-25	106.0	
	Average		180.0	46.1			Average	100.5	0.56
300	17-288	–[3]	165.0	51.2	0	0	15-20	137.0	
300	283	–[3]	159.0	59.1	0	0	15-26	154.5	
300	-	-	-	-	-	-	15-19	143.0	
	Average		162.0	55.1			Average	144.8	0.89
400	6-149[4]	119.0	122.5	53.7	12	53	15-27	142.8	
400	6-147	165.0	175.0	46.1	0	0	17-312	137.0	
	Average	142.0	148.8	49.9			Average	139.5	0.94
500	17-290	166.0	173.0	55.0	0	0	15-28	138.9	
500	6-148[4]	102.0	108.0	42.7	10	54	17-311	145.5	
	Average	134.0	140.5	48.8			Average	142.2	1.01
600	-	-	103.0[5]	-	-	-	171	101.0	
600	17-291	158.8	162.5	46.1	4	5	169	104.5	
600	-	-	-	-	-	-	15-18	119.5	
	Average		133.0				Average	108.3	0.81
700	15-3[4]	93.5	102.2	42.5	9	62	30	109.0	
700	289[4]	92.0	98.0	41.2	8	56	158	114.0	
700	-	-	-	-	-	-	159	97.5	
	Average	92.8	100.1 132.0[6]	41.8	8.5	59.1	Average	106.8	0.81

[1] Warm-rolled and stress-relieved for 10 min at 2100° F.
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min^{-1}.
[3] Fractured before 0.2% offset.
[4] Specimens were electropolished before evaluation; remaining specimens were evaluated in the mechanically-ground condition.
[5] Value determined from unnotched strength curve for mechanically ground - electropolished specimens for calculating the notched/unnotched strength ratio.
[6] This value, which was used for calculation of the notched/unnotched strength ratio at 700° F, was determined by extrapolating the average curve for mechanically ground and electropolished unnotched specimens to 700° F.

Table XIV

Notched-Tensile and Unnotched-Tensile Data for 0.060-In. Tungsten Sheet in the Recrystallized Condition[1] at Moderately-Elevated Temperatures[2]

	Unnotched Specimens						Notched Specimens		
Temp °F	Specimen No.	0.2% Offset Yld. Str. ksi	Ultimate Tens. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Red. of Area %	Specimen No.	Ultimate Tens. Str. ksi	Notched/Unnotched Strength Ratio
200	6-185	–[3]	60.5	67.2	0	0	17-319	30.0	
200	-	-	-	-	-	-	17-308	26.0	
							Average	28.0	0.46
300	17-325	–[3]	>37.8[4]	52.7	0	0	17-314	25.3	
300	-	-	-	-	-	-	17-320	26.0	
							Average	25.6	0.48[5]
400	6-180	–[3]	>50.5[4]	62.9	0	0	15-36	27.5	0.49[5]
500	6-184	–[3]	>70.4[4]	59.5	0	0	6-172	34.7	
500	137	42.0	52.0	39.0	0	2.2	15-32	43.2	
	Average		61.2	49.3			Average	38.9	0.64
600	15-10	–[3]	>74.0	68.9	0	0	15-33	54.7	
600	439	43.0	55.0	43.7	8.2	4.2	-	-	
	Average		64.5	56.3					0.85
700	15-11	64.8	79.0	59.5	7	7	15-34	56.4	
700	-	-	-	-	-	-	313	40.4	
							Average	48.4	0.61
800	17-326	43.5	79.8	49.3	24	15	304	40.4	0.51
900	17-332	42.0	72.4	50.2	12	14	29	38.3	0.53

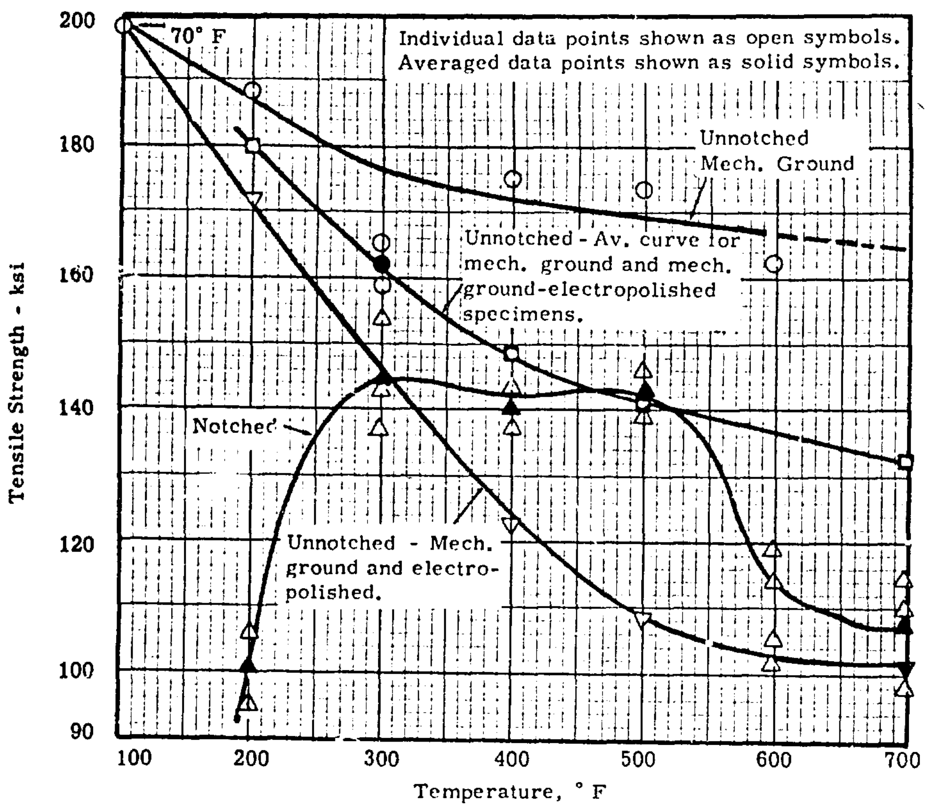
[1] Specimens were recrystallized at 2550° F in 1 hour.
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min^{-1}.
[3] Fractured before 0.2% offset.
[4] Fractured in shoulder across pin hole.
[5] Unnotched tensile strength used to determine the notched/unnotched strength ratio was taken from the unnotched strength curve for 300 and 400° F.

Table XV

Notched-Tensile Transition Temperature for Tungsten Sheet

Condition	Transition Temperature Range, °F
Optimum	200-300
Recrystallized	400-600

The unnotched-tensile strength of the 0.060-in. tungsten in the optimum condition (Figure 29) as determined from mechanically-ground specimens decreased from about 200 ksi at room temperature to about 165 ksi at 600° F, with only a slight increase in ductility. On the other hand, the tensile strength as determined from mechanical-ground-electropolished specimens decreased from about 200 ksi at room temperature to about 107 ksi at 700° F with a substantial increase in ductility. Although it was expected that electropolishing the unnotched specimens would result in greater ductility at lower temperatures, the extent of the increase in ductility and the pronounced decrease in the yield and ultimate tensile strength as compared to the mechanically-ground specimens, at comparable temperatures, was not expected. The electropolishing apparently drastically altered the plastic deformation characteristics of the tungsten sheet. The notched tensile strength for the optimum condition increased significantly, from 105 ksi to 145 ksi, between 200 and 300° F, and remained at approximately 145 ksi up to 600° F, after which the strength decreased to 120 ksi at 700° F. The notched/unnotched tensile-strength ratio for the tungsten sheet in the optimum condition as determined from the averages of notched and unnotched (mechanical-ground and mechanical-ground electropolished specimens) data is given in the lower part of Figure 29. A notch-strength ratio of unity was reached at about 500° F. In the recrystallized condition (Figure 30), the unnotched tensile strength increased from about 50 ksi at 200° F to 80 ksi at 800° F, after which the strength decreased with increasing temperature up to 900° F. As previously mentioned, the recrystallized sheet fractured in a brittle manner up to about 700° F. Consequently the apparent tensile strength, as shown in Figure 30, increased as the testing temperature was increased up to about 700° F. The notched tensile strength for the recrystallized condition increased significantly, from approximately 25 ksi to 55 ksi, between 200 and 600° F, after which the strength decreased to approximately 40 ksi with increasing temperatures up to 900° F. Since most of the recrystallized specimens fractured outside the gage section at temperatures up to 600° F, the notched/unnotched-strength-ratio data are based, to a large extent, on the maximum stress in the gage section at fracture outside the gage section. A notch-strength ratio of unity was not obtained, but at 600° F the ratio was 0.85.



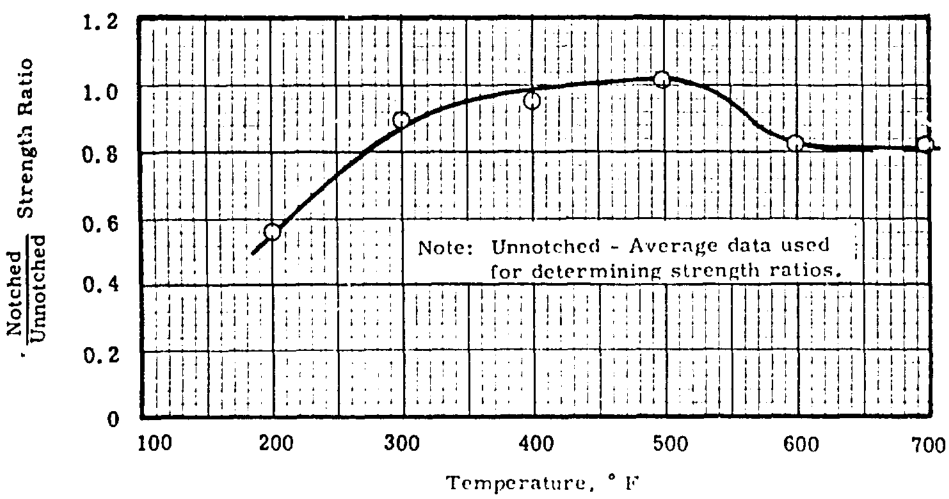


Figure 29. Notched and unnotched tensile strength and notched/ unnotched tensile strength ratio at different temperatures for 0.060-in. tungsten sheet in the optimum condition.

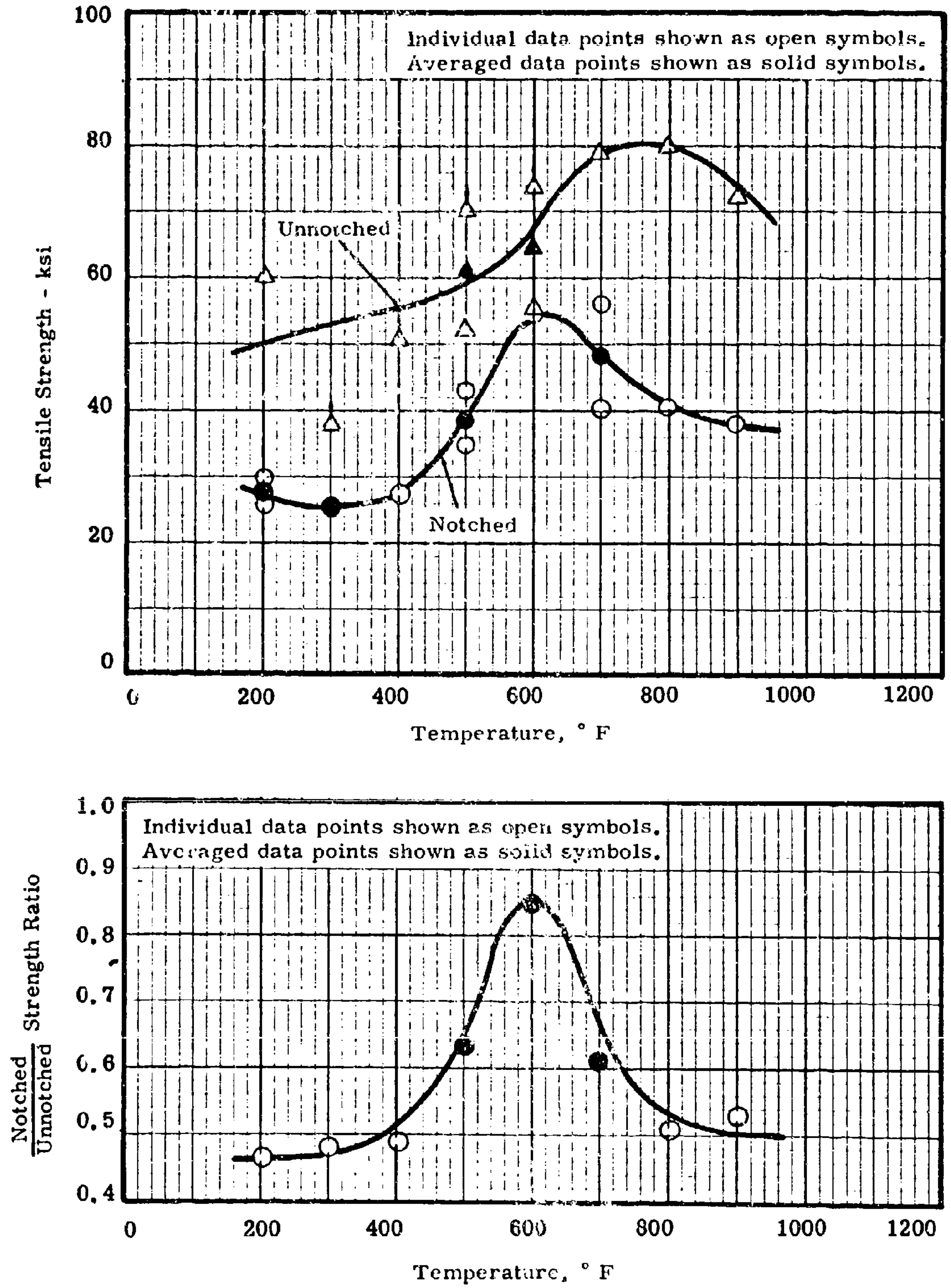


Figure 30. Notched and unnotched tensile strength and notched/unnotched tensile strength ratio at different temperatures for 0.060-in. tungsten sheet in the recrystallized condition.

Bend Properties

The results of initial bend-transition temperature evaluations for both longitudinal and transverse orientations of the optimum 0.060-in. tungsten sheet are summarized in Tables XVI and XVII respectively. These results were obtained with a punch having a radius of 0.090 in. or 1.5 times the sheet thickness (1.5t). Figures 31 and 32 show the bend angle under load plotted as a function of temperature for longitudinal and transverse orientations respectively. Although there is appreciable scatter in the data within each sheet, there was a definite difference in the bend performance of the three sheets. The bend-transition temperature in both orientations was progressively higher for Sheet Nos. 15, 17, and 6 in that order. A greater difference in the bend performance was observed for the transverse orientation than for the longitudinal orientation. Further, the difference in bend performance for the two orientations of each sheet differed. The bend transition for both orientations of Sheet No. 15 was about 350° F, whereas for Sheet No. 6 the transition was at about 400-450° F for the longitudinal direction and 600° F for the transverse direction.

A series of evaluations was conducted with punches of different radii up to 10t (0.60 in.) in an attempt to establish the minimum-bend radius at room temperature for longitudinal direction of sheet in the optimum condition. A maximum bend angle of 15 degrees was made with the 10t punch at room temperature, and with punches of smaller radii the maximum angle was lower. Because of the very limited bend ductility of the tungsten sheet, even with a relatively large punch radius, further attempts were abandoned to determine the minimum bend radius at room temperature. It was decided that more useful information would be obtained from experiments to determine the bend transition temperatures for different bend radii.

The bend-transition temperature was also established with an 8t radius punch for the tungsten sheet in the optimum condition. Table XVIII and Figure 33 show the results of these bend evaluations on longitudinal specimens from Sheet Nos. 15 and 17 at different temperatures. It is apparent that the bend-transition temperature for Sheet No. 15 was about 100° F lower for the 8t bend than it was for the 1.5t bend, whereas the bend-transition temperature of Sheet No. 17 was about the same at the two bend radii.

Upon completion of the initial bend evaluations and in accordance with a recommendation by the Refractory Metal Sheet Rolling Panel, additional bend evaluations were conducted to determine the bend-transition temperature at a bend radius of 4t. The 4t bend-transition-temperature data for the transverse and longitudinal orientations of the 0.060-in. tungsten sheet in the optimum and recrystallized conditions are shown in Tables XIX through XXII and plotted in

Table XVI

Data for Determination of the Bend-Transition Temperature In the Longitudinal Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition - 1.5t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
6	205	375	13	-	-
6	198	400	21	-	-
6	203	400	8	-	-
6	204	425	27	-	-
6	216	425	12	-	-
6	199	450	94+	87	7
6	217	450	88	-	-
6	196	500	94+	87	7
6	197	525	92+	80	12
6	195	600	95+	87	8
15	76	325	6	-	-
15	77	350	95+	94	1
15	78	375	99+	92	7
15	75	388	95+	90	5
15	79	400	102+	92	10
15	55	400	30	-	-
15	62	425	97+	90	7
15	74	425	100+	93	7
15	63	450	85+	79	6
15	59	500	90+	84	6
15	57	525	90+	84	6
15	60	550	98+	91	7
15	56	600	89+	82	7
17	374	300	9	-	-
17	375	325	3	-	-
17	376	350	8	-	-
17	360	375	8	-	-
17	378	375	9	-	-

Table XVI (Continued)

Data for Determination of the Bend-Transition Temperature In the Longitudinal Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition - 1.5t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
17	357	400	24	-	-
17	355	400	49	-	-
17	373	400	97+	91	6
17	362	425	88+	82	6
17	358	500	86+	80	6
17	359	550	93+	87	6

[1] Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[2] Plus (+) after bend angle denotes that specimen did not fracture.

Table XVII

Data for Determination of the Bend-Transition Temperature In the Transverse Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition - 1.5t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2]-Deg.	Bend Angle After Springback Degrees	Springback Angles Degrees
6	243	500	7	-	-
6	259	525	7	-	-
6	260	550	18	-	-
6	241	550	104+	99	5
6	261	575	26	-	-
6	262	587	103+	97	6
6	258	600	103+	97	6
6	244	600	24	-	-
6	238	600	8	-	-
6	247	612	104+	98	6
6	242	625	104+	97	7
6	240	625	14	-	-
6	246	637	102+	96	6
6	245	650	110+	103	7
6	239	700	101+	95	6
15	115	300	10	-	-
15	112	325	5	-	-
15	133	325	6	-	-
15	114	337	104+	97	7
15	109	350	104+	96	8
15	131	350	6	-	-
15	126	362	101+	94	7
15	135	400	101+	95	6
15	108	400	72	-	-
15	110	400	11	-	-
15	111	450	108+	102	6
15	107	500	99+	92	7
15	113	600	92+	85	7
15	106	600	98+	92	6

Table XVII (Continued)

Data for Determination of the Bend-Transition Temperature In the Transverse Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition - 1.5t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
17	412	400	8	-	-
17	410	400	10	-	-
17	409	450	13	-	-
17	411	475	7	-	-
17	416	475	7	-	-
17	413	500	43	-	-
17	414	500	33	-	-
17	429	500	50	-	-
17	430	512	100+	94	6
17	428	525	102+	96	6
17	415	525	10	-	-
17	417	550	104+	98	6
17	408	600	103+	98	5

[1]Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[2]Plus (+) after bend angle denotes that specimen did not fracture.

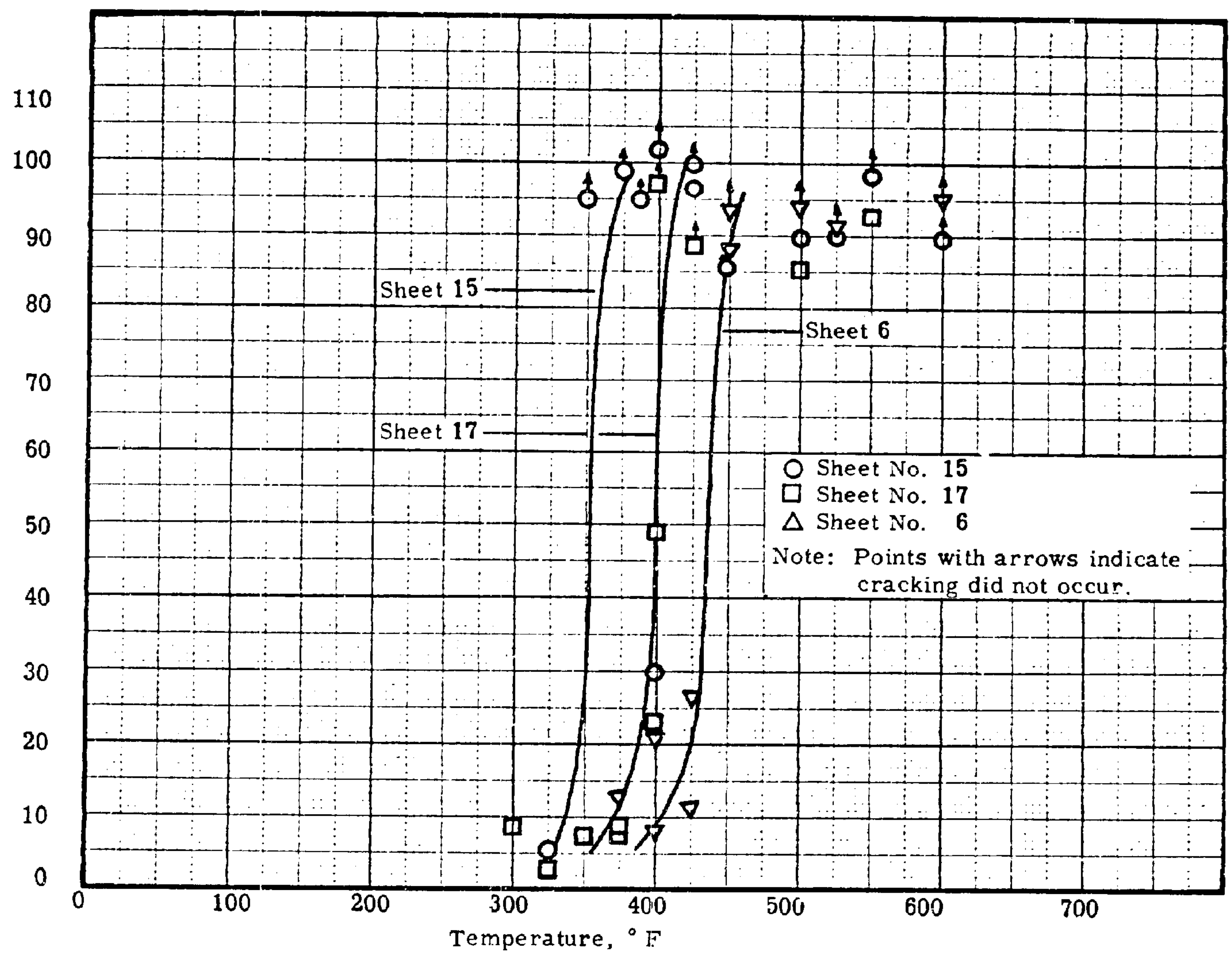


Figure 31. Bend-transition-temperature curves based on bend angle under load for the longitudinal orientation of three 0.060-in.-thick tungsten sheets in the optimum condition using a punch with a radius of 1.5t, a span of 1.5 in., and a ram-rate of 1.0 in./min.

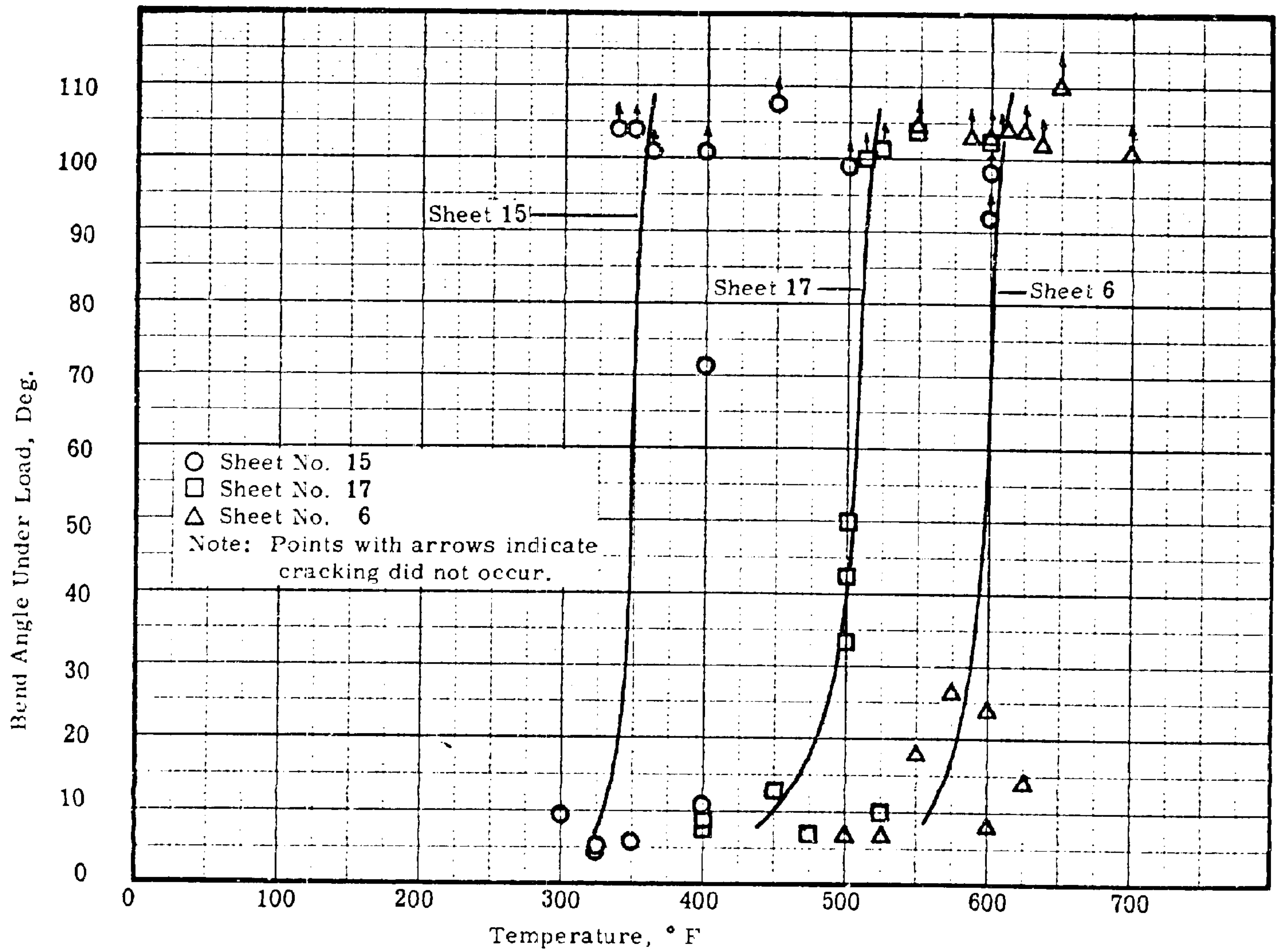


Figure 32. Bend-transition-temperature curves based on bend angle under load for the transverse orientation of three 0.060-in.-thick tungsten sheets in the optimum condition using a punch with a radius of 1.5t, a span of 1.5 in., and a ram-rate of 1.0 in. /min.

Table XVIII

Data for Determination of the Bend-Transition Temperature In the Longitudinal Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition - 8t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2]-Deg.	Bend Angle After Springback Degrees	Springback Angle Degrees
15	87	200	1	-	-
15	89	225	10	-	-
15	90	237	12	-	-
15	88	250	122+	107	15
15	80	262	10	-	-
15	82	275	25	-	-
15	86	300	118+	104	14
17	385	300	7	-	-
17	386	350	6	-	-
17	389	375	22	-	-
17	388	387	21	-	-
17	387	400	122+	108	14
17	382	412	37	-	-
17	381	425	19	-	-

[1]Specimens were heated in air, held 5 min. at temperature, and evaluated at a ram rate of 1.0 in./min.

[2]Plus (+) after bend angle denotes that specimen did not fracture.

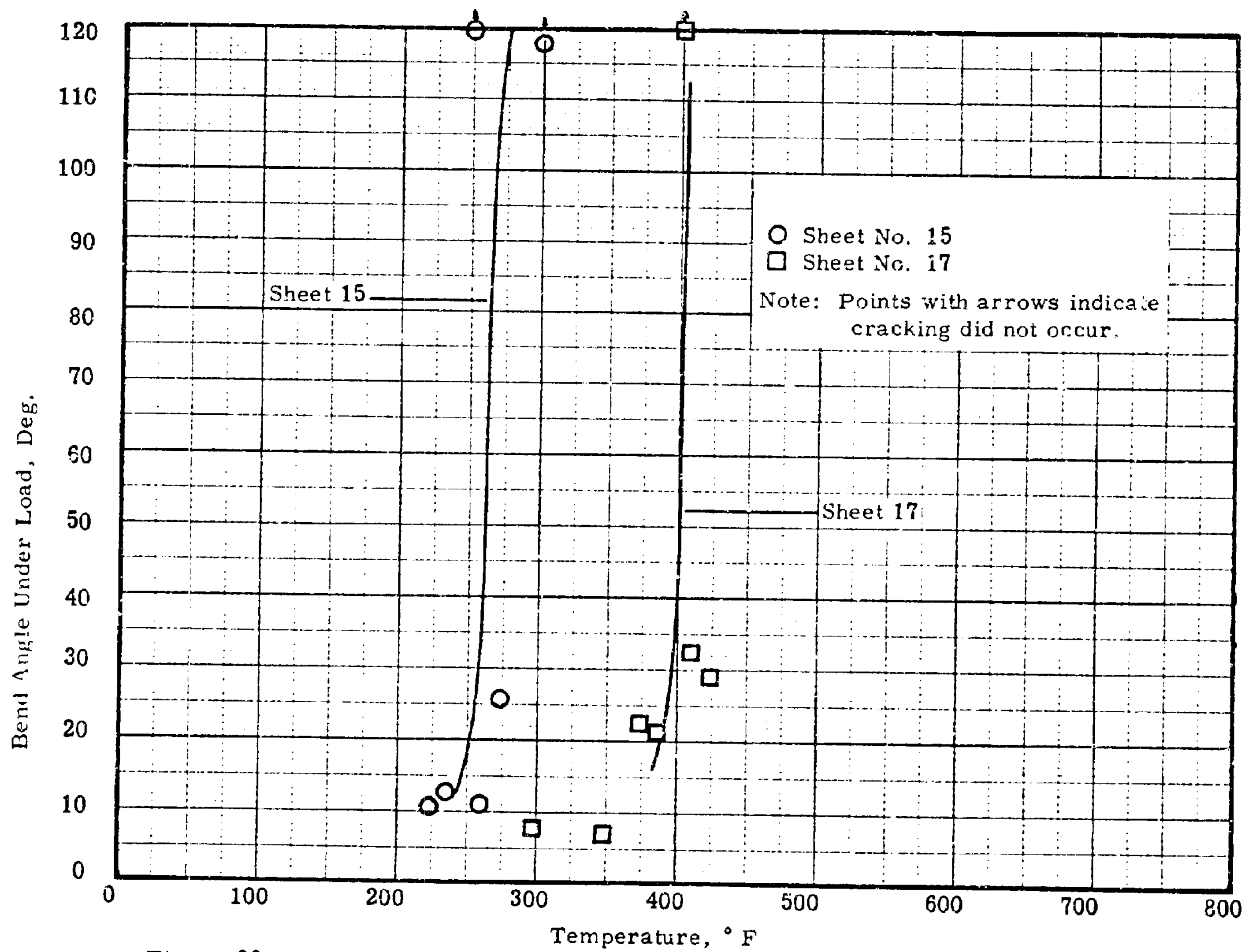


Figure 33. Bend-transition-temperature curves based on bend angle under load for the longitudinal orientation of two 0.060-in.-thick tungsten sheets in the optimum condition using a punch with a radius of 8t, a span of 1.5 in., and a ram-rate of 1.0 in. /min.

Table XIX

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition -4t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	467	300	17	–	–
6	465	325	25	–	–
6	461	350	64	–	–
6	463	375	58	–	–
6	466	375	21	–	–
6	464	388	109+	102	7
6	468	388	22	–	–
6	469	400	35	–	–
6	462	400	105+	99	6
6	460	450	106+	101	5
15	483	100	7	–	–
15	484	175	9	–	–
15	485	200	24	–	–
15	486	212	17	–	–
15	482	225	101+	94	7
15	487	225	64	–	–
15	488	238	20	–	–
15	489	238	74	–	–
15	481	325	99+	94	5
15	480	425	101+	96	5
17	509	225	15	–	–
17	501	250	15	–	–
17	508	275	26	–	–
17	502	300	25	–	–
17	507	300	36	–	–
17	504	312	41	–	–
17	505	312	65	–	–
17	503	325	105+	99	6
17	506	325	105+	98	7
17	500	350	105+	99	6

[1] Specimens were heated in air, held 5 min at temperature, and evaluated at a ram rate of 1.0 in./min.

[2] Plus (+) after bend angle denotes that specimen did not fracture.

Table XX

Data for Determination of the Bend-Transition Temperature in the Transverse Direction for 0.060-In. -Thick Tungsten Sheet in the Optimum Condition -4t Punch Radius[1]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[2] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	479	475	88	–	–
6	471	500	16	–	–
6	478	512	16	–	–
6	477	525	106+	100	6
6	472	550	69	–	–
6	475	550	74	–	–
6	474	562	105+	100	5
6	476	562	24	–	–
6	473	575	106+	101	5
6	470	600	103+	98	5
15	491	250	16	–	–
15	492	300	22	–	–
15	494	312	36	–	–
15	495	312	34	–	–
15	493	325	107+	99	8
15	496	325	62	–	–
15	497	338	31	–	–
15	498	338	110+	102	8
15	490	350	106+	99	7
15	499	375	108+	100	8
17	510	400	6	–	–
17	511	400	21	–	–
17	513	450	34	–	–
17	514	475	13	–	–
17	515	488	20	–	–
17	512	500	110+	103	7
17	516	525	16	–	–
17	518	525	14	–	–
17	519	538	108+	102	6
17	517	550	110+	103	7

[1] Specimens were heated in air, held 5 min at temperature, and evaluated at a ram rate of 1.0 in. /min.

[2] Plus (+) after bend angle denotes that specimen did not fracture.

Table XXI

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction for 0.060-In. -Thick Tungsten Sheet in the Recrystallized Condition - 4t Punch Radius[1,2]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	236	600	6	-	-
6	232	612	8	-	-
6	234	625	42	-	-
6	219	625	93	-	-
6	231	638	38	-	-
6	235	650	101+	96	5
6	218	650	102+	98	4
6	214	650	112+	106	6
6	215	662	104+	99	5
6	237	700	99+	94	5
15	64	400	4	-	-
15	70	425	5	-	-
15	66	450	6	-	-
15	67	475	7	-	-
15	69	488	7	-	-
15	65	500	99+	90	9
15	68	500	95	-	-
15	73	512	106+	94	12
15	72	525	9	-	-
15	81	525	4	-	-
15	71	550	107+	96	11
15	53	600	104+	95	9
15	91	600	107+	101	6
17	379	475	5	-	-
17	363	500	7	-	-
17	380	512	6	-	-
17	372	525	108+	98	10
17	364	550	82	-	-
17	365	550	65	-	-
17	366	575	30	-	-
17	396	625	103+	97	6
17	367	650	42	-	-
17	370	650	77	-	-
17	371	662	103+	97	6
17	395	662	105+	101	4
17	369	675	92+	88	4
17	368	700	94+	91	3

[1] Specimens were heated in air, held 5 min at temperature, and evaluated at a ram rate of 1.0 in./min.

[2] Radius of curvature of bent specimens was approximately 5t.

[3] Plus (+) after tend angle denotes that specimen did not fracture.

Table XXII

Data for Determination of the Bend-Transition Temperature in the Transverse Direction for 0.060-In. -Thick Tungsten Sheet in the Recrystallized Condition - 4t Punch Radius[1,2]

Sheet No.	Specimen No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture[3] Deg.	Bend Angle After Springback Deg.	Springback Angle Deg.
6	256	500	3	-	-
6	254	550	6	-	-
6	266	550	6	-	-
6	257	562	78	-	-
6	265	562	72	-	-
6	255	575	107+	106	1
6	267	575	68	-	-
6	251	600	99+	97	2
6	250	625	110+	105	5
6	249	650	35	-	-
6	263	650	53	-	-
6	264	650	105+	101	4
15	117	500	7	-	-
15	127	525	7	-	-
15	128	538	4	-	-
15	129	538	43	-	-
15	134	550	5	-	-
15	118	550	85	-	-
15	125	550	102+	98	4
15	119	562	7	-	-
15	124	562	18	-	-
15	130	562	101+	96	5
15	132	575	104+	97	7
15	120	575	78	-	-
15	123	575	96+	94	2
15	122	588	95+	92	3
15	116	600	96+	94	2
15	121	650	95+	92	2
17	435	500	6	-	-
17	434	525	4	-	-
17	419	550	6	-	-
17	426	550	4	-	-
17	422	550	8	-	-
17	424	562	24	-	-
17	425	562	70	-	-
17	423	575	104+	97	7
17	432	600	25	-	-
17	420	600	101+	95	6
17	427	600	26	-	-
17	421	625	105+	97	8
17	433	625	105+	101	4
17	418	650	98+	94	4
17	431	650	108+	102	6

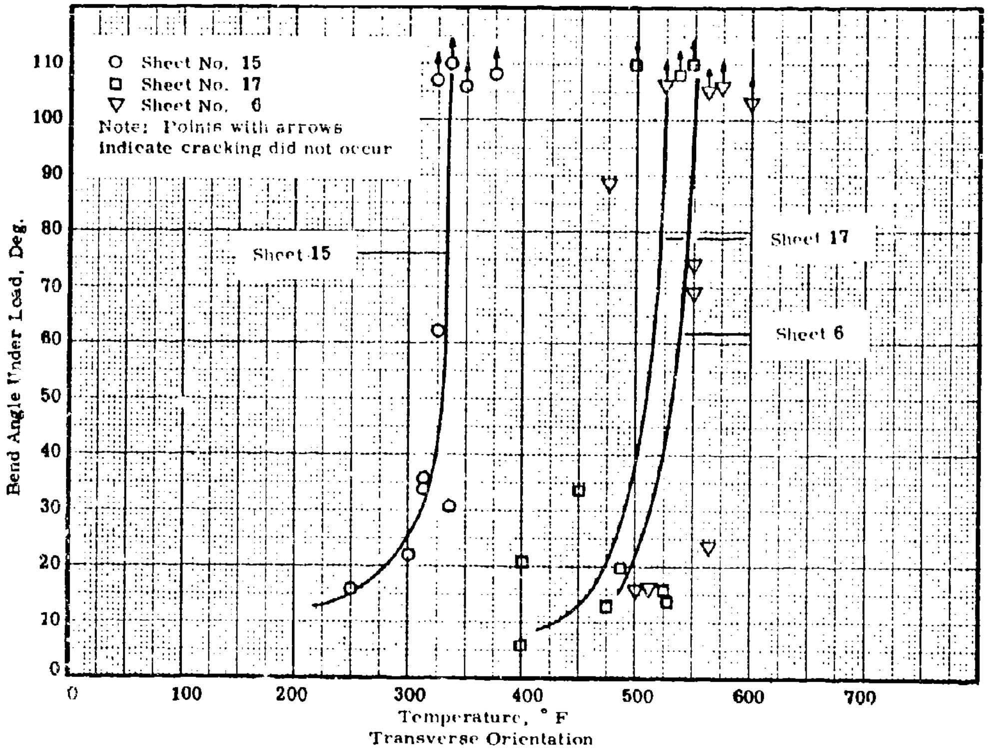
[1] Specimens were heated in air, held 5 min at temperature, and evaluated at a ram rate of 1.0 in./min.
[2] Radius of curvature of bent specimens was approximately 5t.
[3] Plus (+) after bend angle denotes that specimen did not fracture.

Figures 34 and 35. The bend-transition temperature at a radius of 4t was 100 to 200° F lower in the longitudinal than in the transverse direction for the sheet in the optimum condition. However, in the recrystallized condition the transition temperature for the longitudinal direction was only about 50° F lower than for the transverse direction. In general, the bend transition temperature of the recrystallized sheet was about 200 to 300° F higher in the longitudinal direction and about 50 to 200° F higher in the transverse direction than that for corresponding orientations of the sheet in the optimum condition, with significant variations in these differences occurring among different sheets.

Bend-transition data for 1.5t, 4t, and 8t bend-radii are summarized in Table XXIII. This summary shows the bend-transition-temperature ranges for the longitudinal and transverse directions of different sheets in the optimum and recrystallized conditions. The bend-transition temperature for the longitudinal orientation of the optimum sheet was from 50 to 100° F lower for the 4t punch than for the 1.5t punch. For the transverse orientation there was no significant change in the bend-transition temperature for bend radii of 1.5t and 4t. The apparent bend-transition-temperature for the longitudinal direction of Sheets Nos. 15 and 17 in the optimum condition was slightly higher for an 8t-bend than for a 4t-bend rather than logically lower. However, relatively few specimens were evaluated with the 8t punch, which may account for the apparent high 8t bend-transition temperature. It is also possible that cracks were initiated at relatively low temperatures because of the increased statistical probability of over-stressing a potential fracture site in the increased area under high stress with the 8t punch.

Compressive Strength

Results of the compression evaluations on the 0.060-in. tungsten sheet in both the optimum and recrystallized conditions are summarized in Table XXIV. A definite drop-of-beam yield behaviour was observed for the recrystallized sheet, and consequently the strength at the upper yield point was approximately 6.5 psi higher than at the 0.2% offset. The 0.2%-offset-yield strength in compression was lower for the longitudinal orientation than for the transverse orientation in the optimum condition and approximately the same in the recrystallized condition. This difference in the yield strengths between the two orientations in the optimum condition is probably due to the stress reversal between longitudinal rolling and compression testing in the longitudinal direction (the Bauschinger effect). The compressive yield strength was significantly lower for the recrystallized condition than for the optimum condition in both the longitudinal and transverse directions. The data indicate that the compressive yield strength of Sheet No. 6 was lower than for Sheet Nos. 15 and 17, the difference being greatest in the recrystallized condition. This difference in



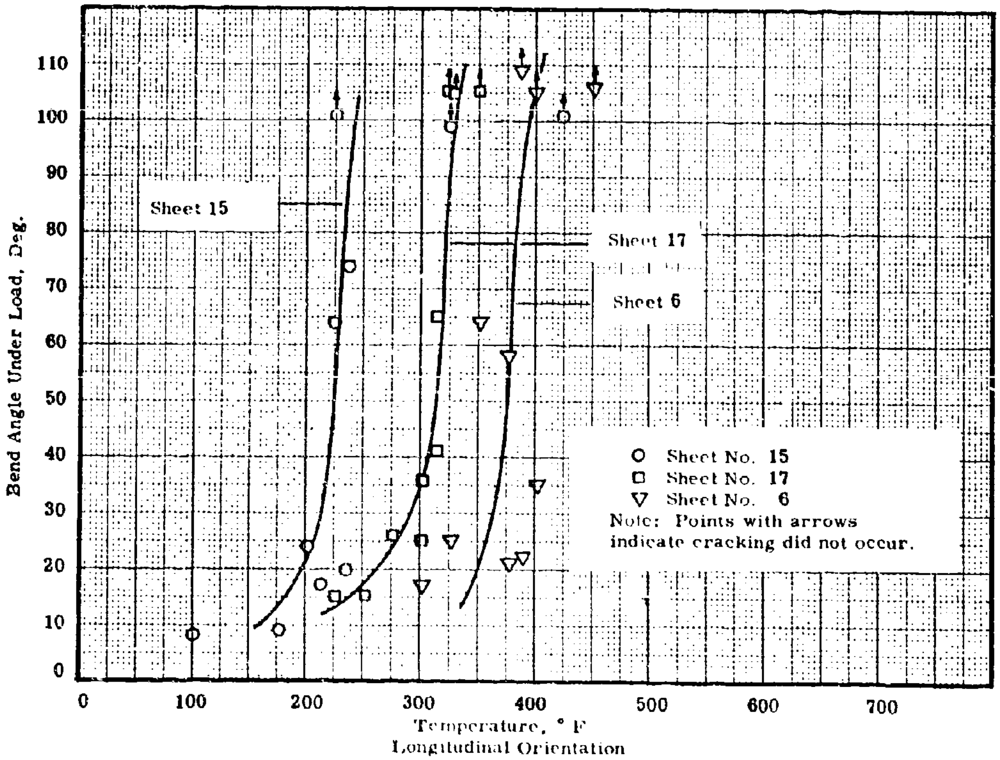
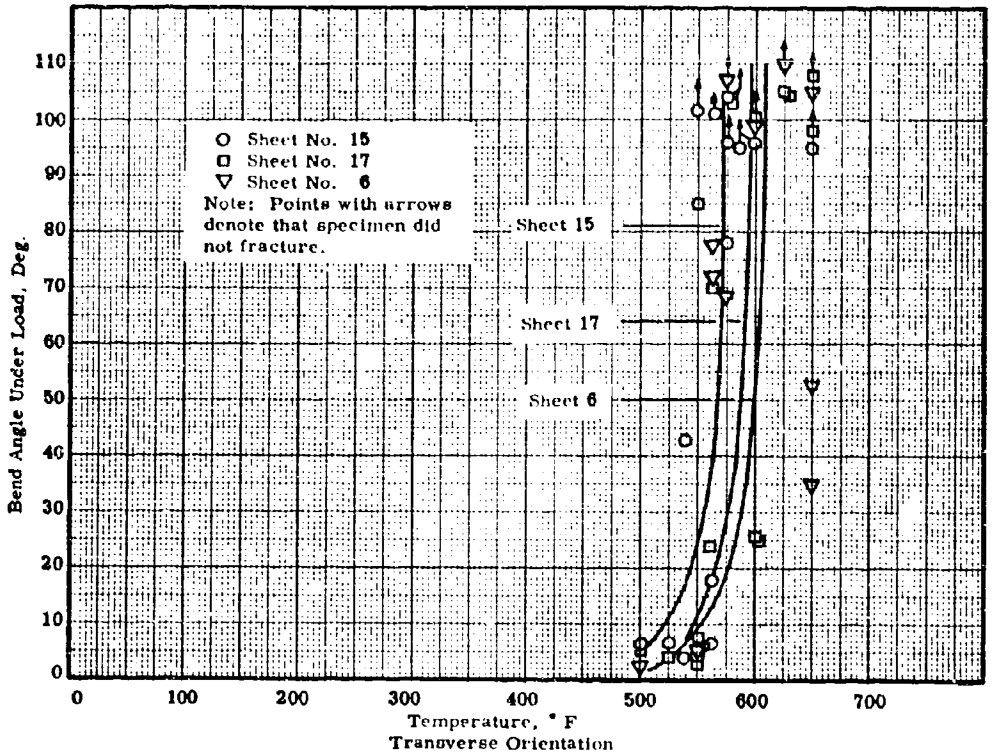


Figure 34. Bend transition-temperature curves based on bend angle under load for the longitudinal and transverse orientation of three 0.060-in.-thick tungsten sheets in the optimum condition using a punch with a radius of 4t, a span of 1.5 in., and a ram rate of 1.0 in./in./min.



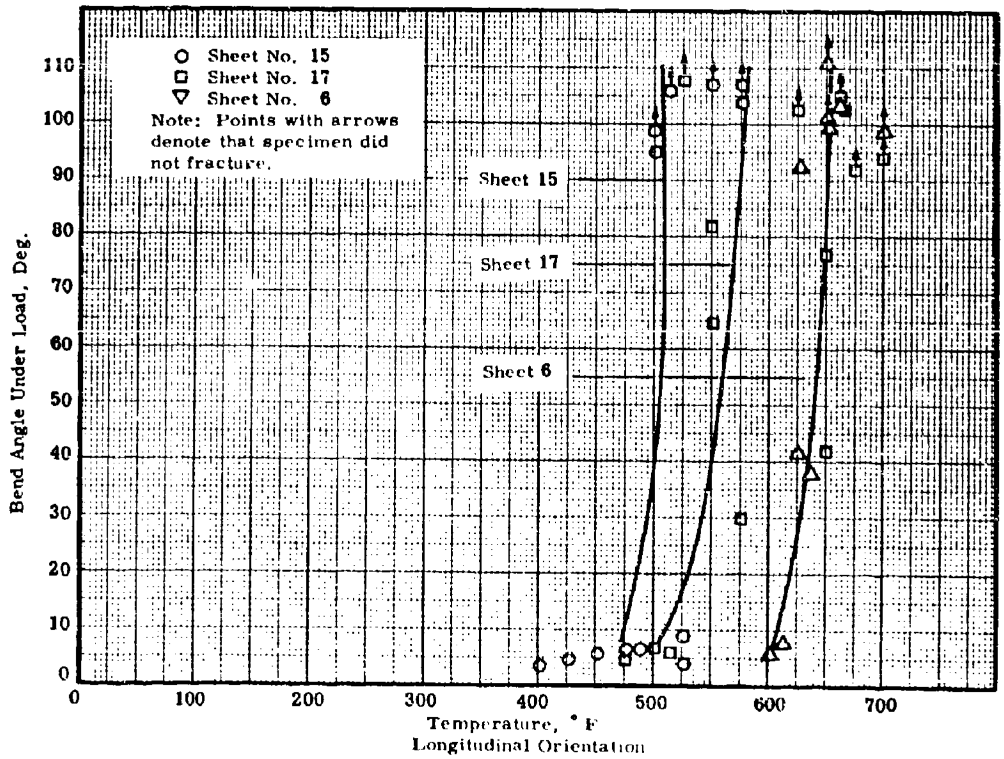


Figure 35. Bend-transition temperature curves based on bend angle under load for the longitudinal and transverse orientation of three 0.060 in -thick tungsten sheets in the recrystallized condition using a punch with a radius of 4t, a span of 1.5 in., and a ram rate of 1.0 in./in./min.

Table XXIII

Summary of Bend-Transition Temperatures for
0.060-In. -Thick Tungsten Sheet

		Bend-Transition Temperature, °F			
	Sheet	Optimum Condition		Recrystallized Condition	
Punch	No.	Long	Trans.	Long	Trans.
1.5t	15	350-400	337-350	-	-
1.5t	17	400	512-525	-	-
1.5t	6	425-450	550-625	-	-
4t	15	225-237	325-337	500-525	550-575
4t	17	300-325	500-525	525-650	575-600
4t	6	387-400	525-562	650-638	575-650
8t	15	250-275	-	-	-
8t	17	400-425	-	-	-

Table XXIV

Longitudinal and Transverse Compression Properties at Room Temperature of 0.060-In.-Thick Tungsten Sheet in the Optimum[1] and Recrystallized[2] Conditions

Orientation	Optimum Condition				Recrystallized Condition			
	Sheet No.	Spec. No.	0.2%-Offset Yld. Str. ksi	Mod. of Elasticity 10^6 psi	Sheet No.	Spec. No.	0.2%-Offset Yld. Str.[3] ksi	Mod. of Elasticity 10^6 psi
Long.	6	458	176.7	46.0	6	192	130.5	49.2
Long.	15	101	190.6	45.4	6	193	132.0	65.8
Long.	15	102	191.2	42.6	15	457	154.0	54.5
Long.	17	404	186.4	42.1	17	407	151.0	53.7
Average			186.2	44.0			141.9	55.8
Trans.	6	459	201.0	47.9	6	271	127.2	58.0
Trans.	15	139	219.0	43.2	6	273	127.0	55.8
Trans.	17	441	210.8	46.6	15	455	144.3	52.6
Trans.	17	442	209.6	42.0	17	456	160.5	55.5
Average			210.1	44.9			139.8	55.5

[1] Warm-rolled and stress-relieved at 2100° F.
[2] Recrystallized for 60 min at 2550° F.
[3] Upper field point approximately 6.5 psi higher than at 0.2% offset.

strength between the sheets is probably related to the differences in the microstructure, which were apparent for the sheet in the as-received condition (Figure 1) and after recrystallization (Figure 23). The modulus of elasticity in compression in both orientations for the optimum condition was lower than for the recrystallized condition, as was observed for the tensile modulus at room temperature.

The results of the elevated temperature compression tests on the 0.060- and 0.100-in. tungsten sheet are summarized in Table XXV. The apparent low yield strength and compressive modulus values at 1800° F may have been caused by yielding within parts of the compression test apparatus. No useful data were obtained from evaluations attempted on the 0.020-in. sheet at 600 and 750° F due to lamination and bending of the specimens at low load levels. This series of evaluations indicated that the compressive yield strength and modulus of elasticity of tungsten sheet was lower than comparative tensile properties at the same temperatures. The lower compressive yield strength may be a manifestation of the stress-reversal as observed in the room temperature data.

Shear and Bearing

Two shear specimens evaluated at room temperature exhibited brittle failure in tension rather than failing along the shear plane (Figure 14). The loads recorded at failure were 700 and 980 lb, which correspond to shear stresses of 59.5 and 84.8 ksi, however it is probably that the ultimate shear stress is considerably higher. Since the shear tests at room temperature were found to be impractical on the tungsten sheet, because of the brittleness of the material, the remaining shear and all bearing evaluations were conducted at slightly elevated temperatures in an attempt to promote deformation and fracture in the desired section or zone of the specimens. Results of the shear and bearing evaluations of the 0.060-in. tungsten sheet in the optimum condition are summarized in Tables XXVI and XXVII respectively. This summary shows the ultimate shear strength of the tungsten sheet to be approximately 49.5 ksi at 400° F, which is about one-third of the ultimate tensile strength (Table XIII) obtained at this temperature. For most materials, the shear strength is generally from one-half to two-thirds of the ultimate tensile strength. The bearing data indicate that at 300° F the bearing yield strength at 2% deformation of the bearing-hole diameter was slightly higher and the ultimate bearing strength lower than at 500° F. The lower ultimate strength is probably due to the material being significantly less ductile at 300° F.

Table XXV

Compression Properties of Tungsten Sheet at Elevated Temperature[1]

Sheet Thickness In.	Temperature °F	0.2% Offset Yld Str, ksi	Mod. of Elasticity 10^6 psi
0.060	900	79.8	33
0.060	900	63.0	27
Avg		71.4	30
0.060	1500	50.0	28
0.060	1500	47.5	27
Avg		48.7	28
0.100	1200	61.5	30
0.100	1200	60.3	29
Avg		60.9	30
0.100	1800	14.9[2]	19[2]
0.100	1800	14.9[2]	17[2]
Avg		14.9	18

[1] Specimens were heated to the desired temperature inside a split tube furnace in an argon atmosphere and loaded at a strain rate of approximately 0.005 in./in./min.

[2] Low yield and modulus data possibly due to yielding of compression test apparatus.

Table XXVI

Shear Strength of 0.060-In. Tungsten Sheet[1]

Temp., °F	Shear Strength[2] ksi	Remarks
70	>59.5	Tensile fracture
70	>84.8	Tensile fracture
300	>97.5	Tensile fracture
400	49.5	Fractured on shear plane

[1] Optimum condition
[2] Based on area = shear path distance x sheet thickness.

Table XXVII

Bearing Strength of 0.060-In. Tungsten Sheet[1]
(e/D = 1.5)

Temp., °F	Bearing Str.[2] at 2% Offset ksi	Ultimate Bearing Str.[2] ksi	Percent Deformation at Fracture	Remarks
300	-	>155.0	0	Tensile fracture
300	222.0	242.0	4.0	Bearing fracture
400	203.8	264.5	Approx 18.1	Bearing fracture

[1] Optimum condition.
[2] Based on area = sheet thickness x bearing hole diameter.

Creep

The primary objective of the creep tests was to determine the stress level required to produce 1% total deformation at a given temperature in approximately 100 hours. Creep specimens of the 0.060-in. tungsten sheet in the optimum condition were loaded to different stress levels at 2500° F to produce 1% total deformation in times ranging up to approximately 150 hours. Time-deformation curves for each evaluation are shown in Figure 36. The time to produce the required 1% deformation was read from these curves as recorded in Table XXVIII and plotted against stress in Figure 37. Based on the time-stress curve in Figure 37, the critical stress for 1% creep deformation in 100 hours at 2500° F was 6.3 ksi.

Table XXVIII

Time for 1% Creep Deformation of 0.060-In. Tungsten Sheet at 2500° F and Different Stress Levels[1]

Stress, ksi	Time, hr
10.0	2.5
8.0	4.9
7.8	13.4
7.0	72.0
6.4	77.9
6.0	149.0

[1] Optimum condition; longitudinal orientation.

Thermal Stability

Tensile evaluations were performed at room temperature and 800° F on all 0.060-in. tungsten creep specimens in the optimum condition after 1.0% plastic deformation at 2500° F. The results of these evaluations are summarized in Table XXIX. The material after creep exposure was extremely brittle at room temperature, which probably indicates that the optimum structure had, to some extent, recrystallized during creep at 2500° F. Therefore, the remaining specimens were tested at 800° F for comparison at the same temperature to the tensile properties of the recrystallized sheet. The limited information obtained from these evaluations prevented any real appraisal of the thermal

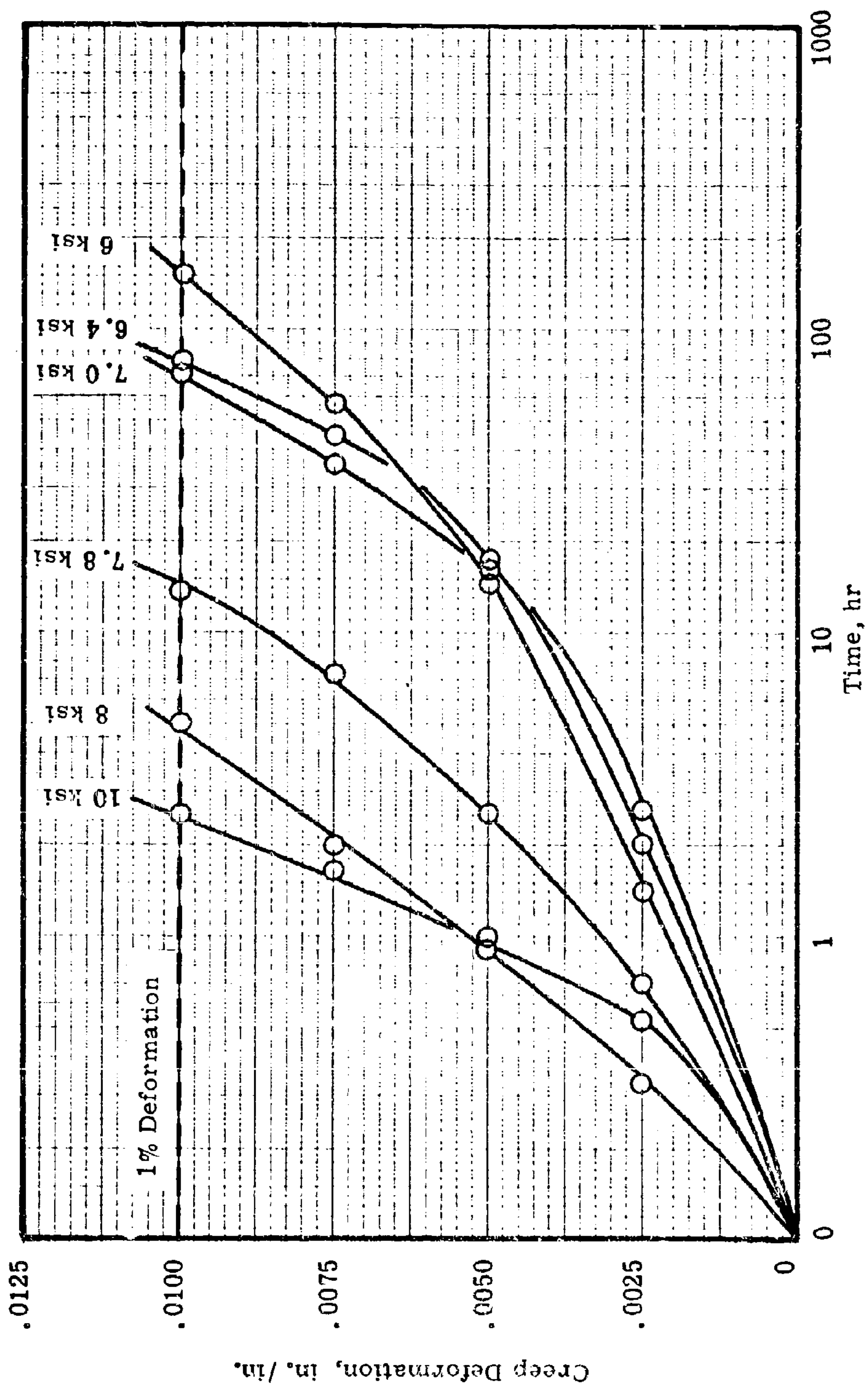


Figure 36. Time-deformation curves for 0.060-in.-thick tungsten sheet at 2500° F and different stresses

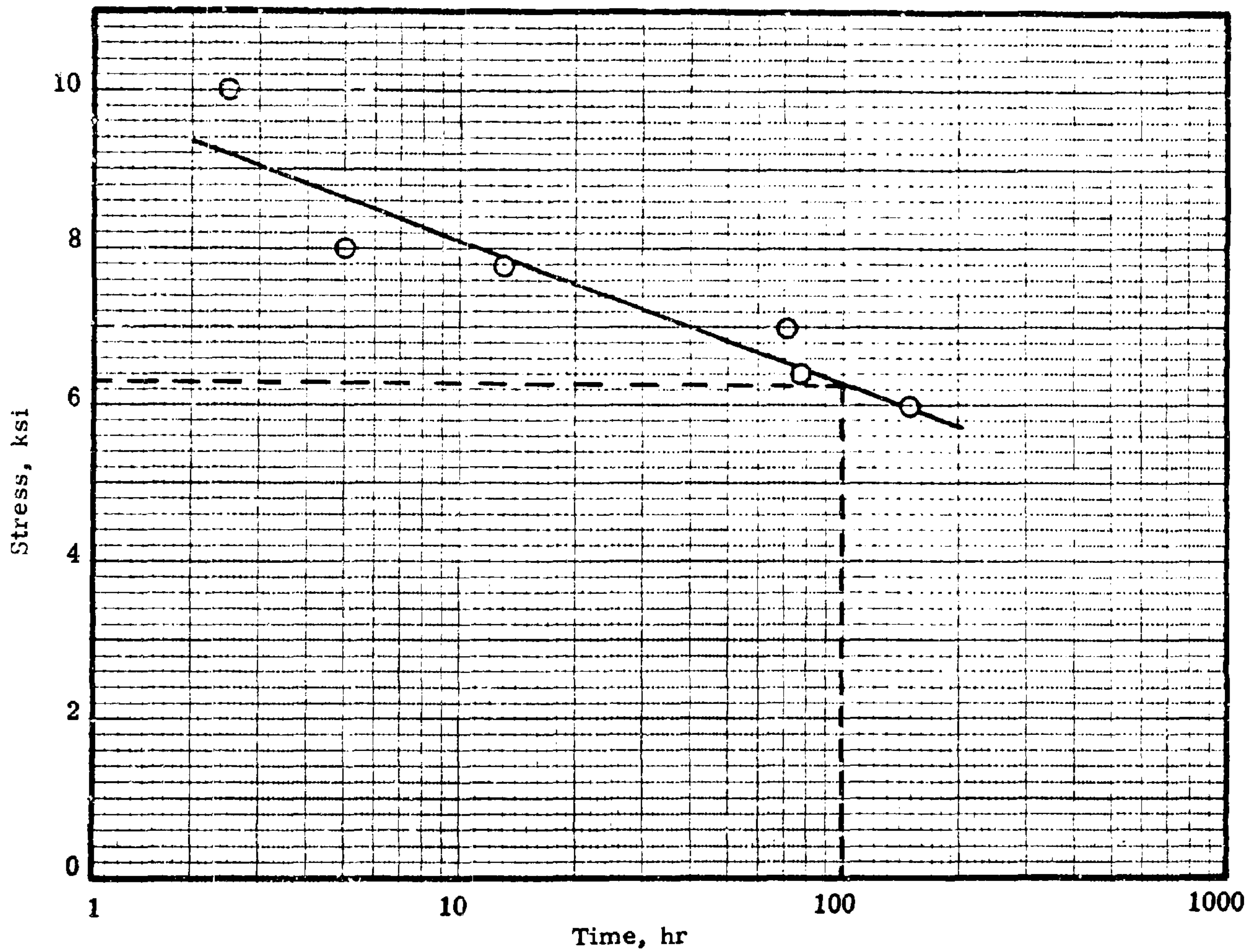


Figure 37. Effect of stress on time to 1% creep deformation at 2500° F for 0.060-in. tungsten sheet.

Table XXIX

Tensile Properties of the Tungsten Sheet After Creep Exposure to 1% Deformation at 2500° F[1]

Creep Data							
Stress ksi	Time in hr to 1%	Temp., ° F	0.2%-Offset Yld. Str., ksi	Ultimate Tens. Str., ksi	Elongation in 1 in. %	Red. of Area, %	Remarks
6.4	77.9	75	—[2]	>51.3	—	—	Fractured outside of gage section
7.0	72.0	75	—[2]	>64.2	—	—	Fractured outside of gage section
6.0	149.0	800	14.3	>42.7	9.0	0	Fractured outside of gage section
7.8	13.4	800	16.9	54.1	60.0	65.0	Fractured inside of gage section
8.0	4.9	800	—[2]	>37.1	—	—	Fractured outside of gage section
10.0	2.5	800	—[2]	>30.9	—	—	Fractured outside of gage section

[1] Optimum condition and longitudinal direction.
[2] Fractured before 0.2%-offset yield.

stability of this material. However, it is evident that the creep exposure had a detrimental effect on the normal tensile properties of the tungsten sheet in the optimum or recrystallized conditions, with the strength and ductility being lower than the same properties of the unexposed-and-undeformed sheet in either condition. The tensile properties for unexposed sheet in the optimum and recrystallized conditions were shown in Tables IX and XIV respectively.

Density

The results of density measurements from the different sheets and gages of the tungsten sheet material are given in Table XXX.

Table XXX

Density of Tungsten Sheet[1]

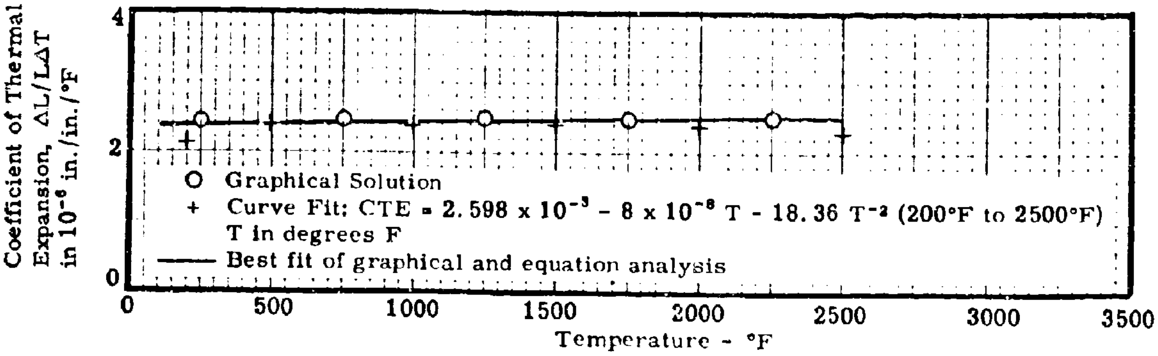
Sheet No.	Sheet Thickness, in.	Density g/cc
6	0.060	19.21
15	0.060	19.18
17	0.060	19.22
112	0.100	19.23

[1] Measurements were made at 26.3° C (79.3° F)

Thermal Expansion

The thermal expansion of the tungsten sheet was determined to 2500° F as shown in Figure 38. The basic data are given in Tables i-b and ii-b of Appendix B. The total thermal expansion from room temperature to 2500° F was about 5.9×10^{-3} in./in. As shown in Figure 38, the expansion of the tungsten was about 10% lower at 2500° F than indicated by some literature data for tungsten, but was about 50% higher than the thermal expansion of arc-cast tungsten determined in earlier work at SRI. The differences probably are due to such factors as composition and thermal history. The rolled sheet for this program was produced by powder-metallurgy processes and was in the stress-relieved condition. The least squares curve fit of the expansion data from Runs 1 through 4 (see Tables i-b and ii-b) resulted in the following equation for thermal expansion:

$$\Delta L/L = 2.598 \times 10^{-3}T - 4 \times 10^{-8}T^2 + 8.500T^{-1} - 0.3059 \qquad \text{(c)}$$



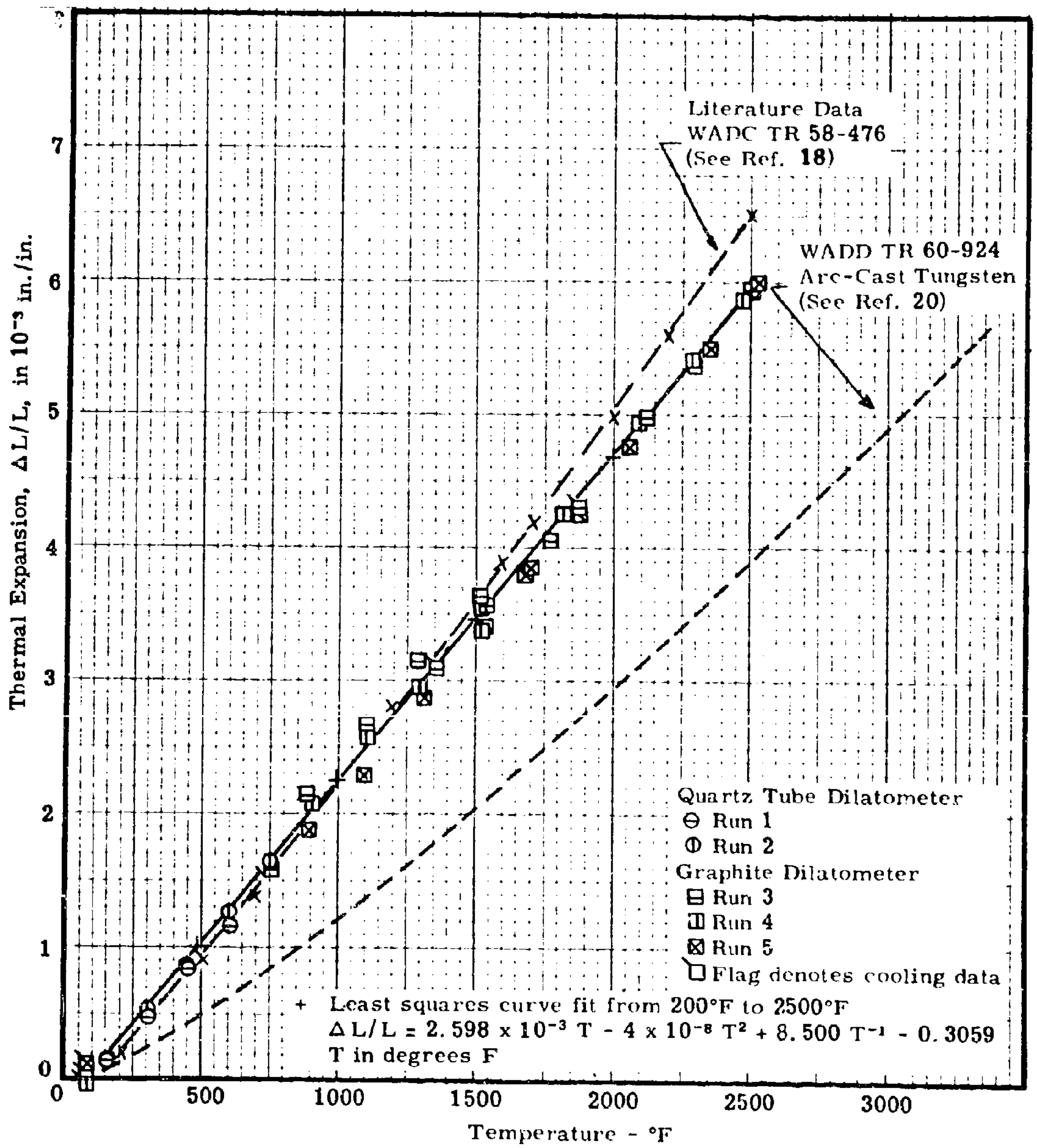


Figure 38. Thermal expansion of tungsten sheet parallel to the plane of the sheet

The temperatures are in degrees Fahrenheit. This equation is valid over the temperature range from 200° F to 2500° F. Run 5 was made to confirm the earlier data. The data from this run were not included in the equation analysis; however, the inclusion of these additional data would not significantly change the results.

The coefficient of thermal expansion (CTE) was determined graphically and by adjusting the derivative of Equation (c) as discussed earlier. The resulting equation for the coefficient of thermal expansion was:

$$CTE = 2.598 \times 10^{-3} - 8 \times 10^{-8} T - 18.36 T^{-2} \quad \text{(d)}$$

This equation is valid from about 200° F to 2500° F. Points calculated using both equations are plotted with the experimental data in Figure 38. The curve for coefficient of thermal expansion represents the best fit of the graphical and mathematical solutions. This coefficient was essentially constant, increasing from about 2.4×10^{-6} in./in./° F at 100° F to about 2.5×10^{-6} in./in./° F at 2500° F.

Thermal Conductivity

The thermal conductivity of the tungsten sheet is shown in Figure 39 and the data are given in Tables iii-b and iv-b of Appendix B. The conductivity decreased from about 1225 $Btu/hr/ft^2/°F/in.$ at 100° F to about 880 $Btu/hr/ft^2/°F/in.$ at 1000° F. Above 1000° F, the conductivity decreased less with increasing temperature, reaching a value at 3000° F of about 710 $Btu/hr/ft^2/°F/in.$ As shown in Figure 39, the conductivity of the tungsten sheet at 100° F was about 10 percent higher than most literature values for tungsten, and from 1000° F to 3000° F the conductivity was in excellent agreement with the "recommended values" published by Powell of the Thermophysical Properties Research Center (17).

Heat Capacity

Enthalpy data are given in Table v-b of Appendix B. The enthalpy and heat-capacity curves for the tungsten sheet are shown in Figure 40. The heat capacity increased from 0.033 Btu/lb/° F at 100° F to about 0.045 Btu/lb/° F at 3000° F. A least squares treatment of the enthalpy data resulted in the following equation for the enthalpy of tungsten sheet from about 32° F to 2900° F:

$$h_{32} = 1.303 \times 10^{-2} T + 483 \times 10^{-8} T^2 - 5871 T^{-1} + 4.449 \quad \text{(e)}$$

Enthalpies calculated with this equation are plotted in Figure 40 and tabulated in Table vi-b.

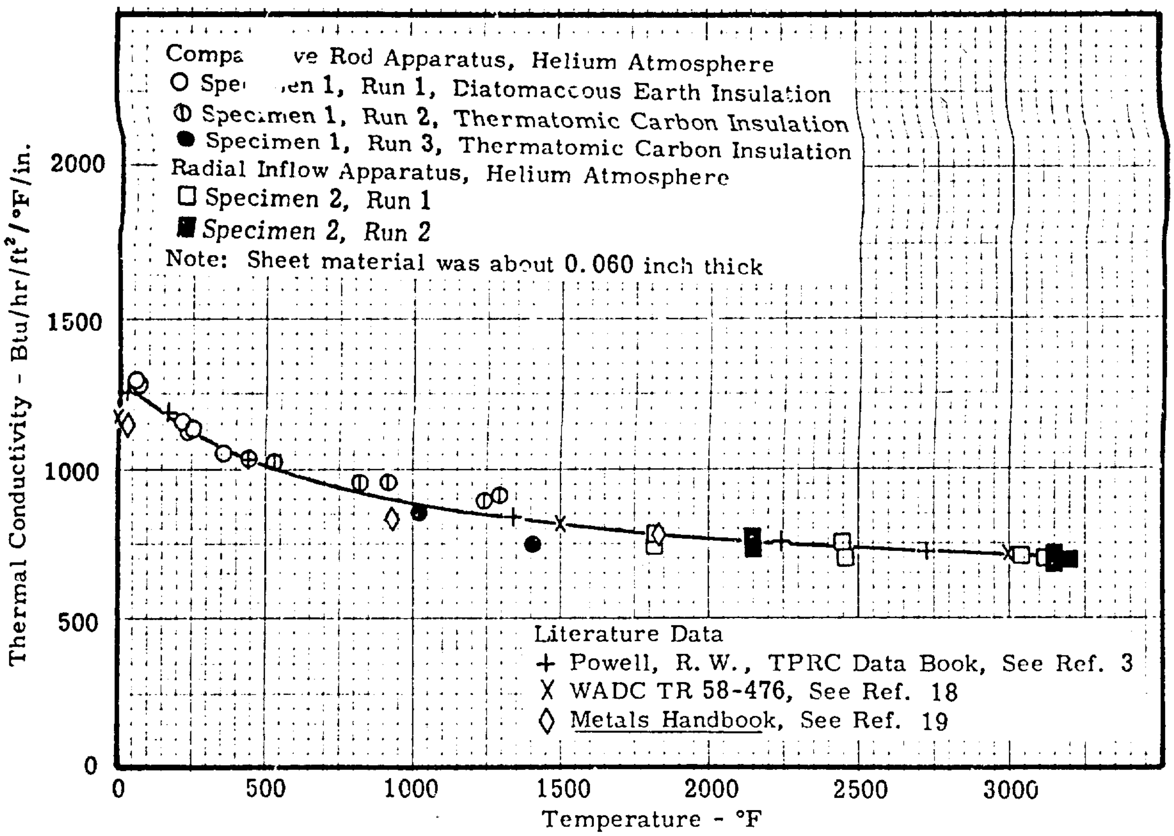


Figure 39. Thermal conductivity of tungsten sheet parallel to the plane of the sheet

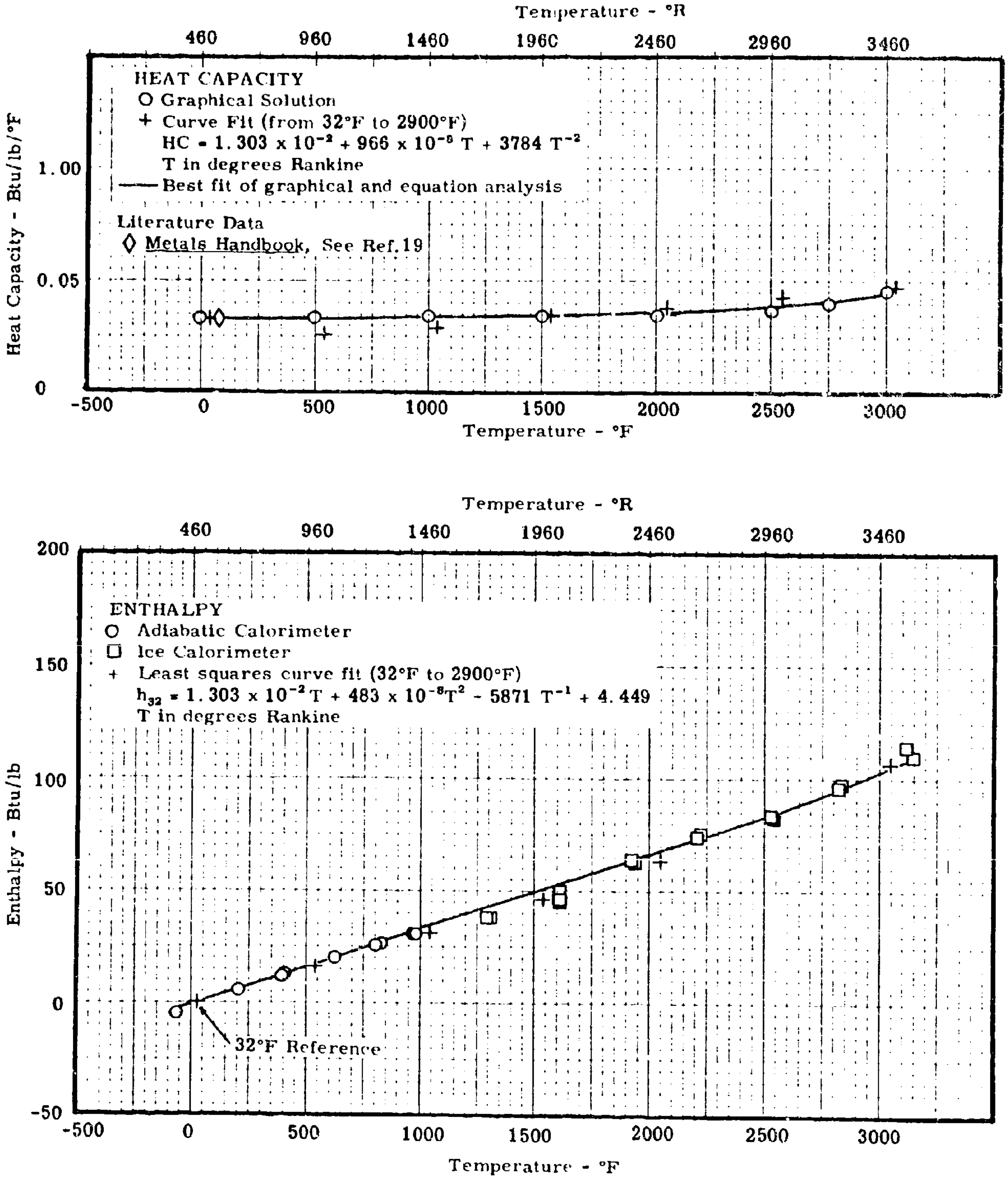


Figure 40. The heat capacity and enthalpy of tungsten sheet

The derivative of the equation (e) was adjusted to agree with the graphically determined heat capacity at 500° R (40° F) to obtain the following equation for heat capacity:

$$HC = 1.303 \times 10^{-2} + 966 \times 10^{-8}T \times 3784T^{-2} \qquad \text{(f)}$$

This equation is valid from about 32° F to 2900° F. Points calculated with this equation are also plotted in Figure 40 and the heat capacities calculated with this equation are compared to the graphical solutions in Table vi-b. The curve for heat capacity in Figure 40 represents the best fit of the values determined from the equation and from the graphical solution. The heat capacity of the tungsten sheet at room temperature was in good agreement with the data for tungsten from several literature sources (18, 19).

Properties of the TZM Sheet

Recrystallization Temperature

Results of the hardness measurements and estimates of the percent of recrystallized structure are summarized in Tables XXXI through XXXIII and Figures 41 through 46. Figures 41, 42, and 43 show respectively for the 0.020-in., 0.040-in., and 0.060-in. TZM sheet the Rockwell hardness at the surface of the sheet and the DPH at the midthickness of the sheet as functions of temperature for 5 and 60 minute hold times. Figures 44, 45, and 46 show the estimated percent of recrystallized structure as a function of temperature for the two different hold times and the three different sheet thicknesses. The microstructure on longitudinal and transverse sections of the as-received sheet and on longitudinal sections after the different hold times at various temperatures are shown in Figures 44, 45, and 46. The recrystallization temperature, based on recrystallization of the microstructure and on the DPH at the midthickness, for the different gages of the TZM sheet were determined as shown in Table XXXIV:

Table XXXIV

Recrystallization Temperature of the TZM Sheet

Sheet Thickness, In.	Recrystallization Temperature Based on: Recrystallization of Structure	Recrystallization Temperature Based on: DPH at Mid-thickness of Sheet
0.020	2400° F	2390° F
0.040	2350° F	2360° F
0.060	2355° F	2350° F

Table XXXI

Hardness and Percent Recrystallization of 0.020-In. TZM Sheet[1]
After Holding for Five and Sixty Minutes at Different Temperatures

	Time at Temperature - Min					
	5			60		
Temp °F	DPH[2]	15-T Hardness[3]	% Recrystallization	DPH[2]	15-T Hardness[3]	% Recrystallization[4]
2000	299	92.2	0	288	92.7	0
2200	295	93.0	0	292	91.5	0
2300	-	-	-	292	92.1	1
2350	-	-	-	282	92.4	8
2400	285	92.8	1	222	88.3	58
2450	257	91.8	8	205	88.1	100
2500	231	88.3	78	191	86.6	100
2550	205	87.5	98	-	-	-
2600	195	86.9	100	-	-	-
2650	195	87.1	100	-	-	-
2800	186	86.5	100	189	85.9	100

[1] Sheet No. 74

[2] Measured on cross section of sheet with a 1 kg load - average of 5 readings.

[3] Measured on surface of sheet on Rockwell 15-T scale - average of 5 readings.

[4] Averaged estimates of two observers.

Table XXXII

Hardness and Percent Recrystallization of 0.040-In. TZM Sheets After Holding for Five and Sixty Minutes at Different Temperatures

		Time at Temperature - Min					
		5			60		
Sheet No.	Temp. °F	DPH[1]	R_a Hardness[2]	% Recrystallization[3]	DPH[1]	R_a Hardness[2]	% Recrystallization[3]
55	2000	291	65.6	0	299	64.6	0
55	2200	289	64.3	<1	299	64.9	<1
55	2300	-	-	-	299	64.9	1
55	2325	-	-	-	280	63.8	4
55	2350	-	-	-	226	56.3	45
55	2400	278	64.8	6	198	54.6	88
55	2450	251	60.7	35	-	-	-
55	2500	225	58.6	60	191	55.0	100
55	2550	199	55.9	90	-	-	-
55	2600	186	54.3	100	200	54.2	100
55	2700	186	53.9	100	-	-	-
55	2800	181	52.8	100	188	51.4	100
56	2300	-	-	-	284	63.0	1
56	2325	-	-	-	264	60.2	20
56	2400	274	63.4	3	192	52.5	98
56	2450	244	58.6	35	-	-	-
56	2500	201	54.1	92	-	-	-
56	2600	193	52.8	100	-	-	-

[1] Measured on cross section of sheet with a 1 kg load - average of 5 readings.

[2] Measured on surface of sheet on Rockwell A scale - average of 5 readings.

[3] Averaged estimate of 2 observers.

Table XXXIII

Hardness and Percent Recrystallization of 0.060-In. TZM Sheet[1] After Holding for Five and Sixty Minutes at Different Temperatures

	Time at Temperature - Min.					
	5			60		
Temp. °F	DPH[2]	Ra Hardness[3]	% Recrystallization[4]	DPH[2]	Ra Hardness[3]	% Recrystallization[4]
2000	305	65.5	0	295	64.4	0
2200	307	65.3	0	303	64.9	< 1
2300	–	–	–	285	63.0	9
2350	302	64.3	3	224	63.2	38
2400	287	64.0	12	202	56.0	82
2450	255	62.6	38	195	56.2	90
2500	220	57.1	90	199	54.1	100
2600	198	55.8	100	197	55.1	100
2800	194	55.7	100	191	54.4	100

[1] Sheet No. 23

[2] Measured on cross section of sheet with a 1 kg load - average of 5 readings.

[3] Measured on surface of sheet on Rockwell A scale - average of 5 readings.

[4] Averaged estimates of two observers.

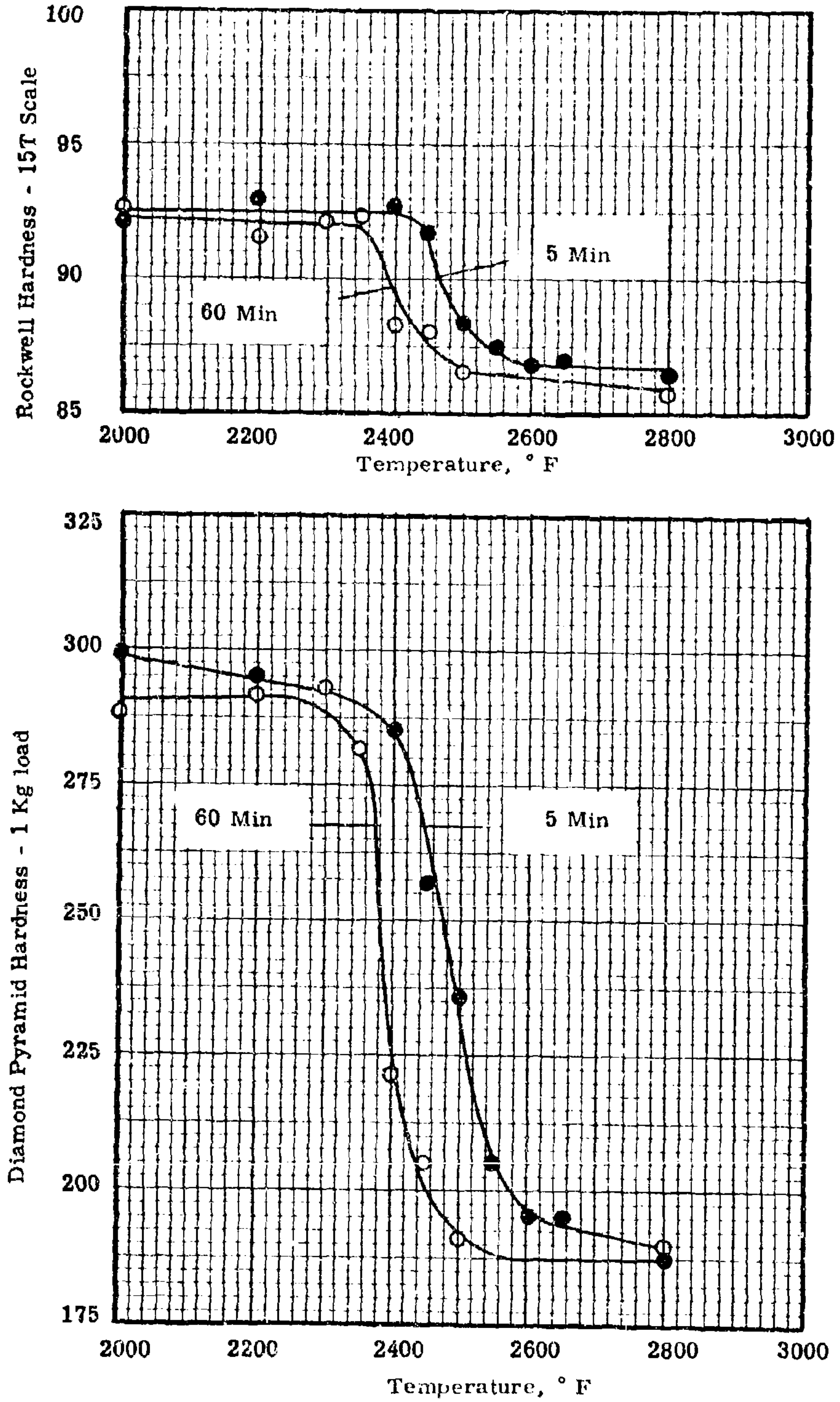


Figure 41. The effect of temperature and time at temperature on the surface hardness and cross-section hardness of 0.020-in. TZM sheet. Each data point shown represents the average of five readings.

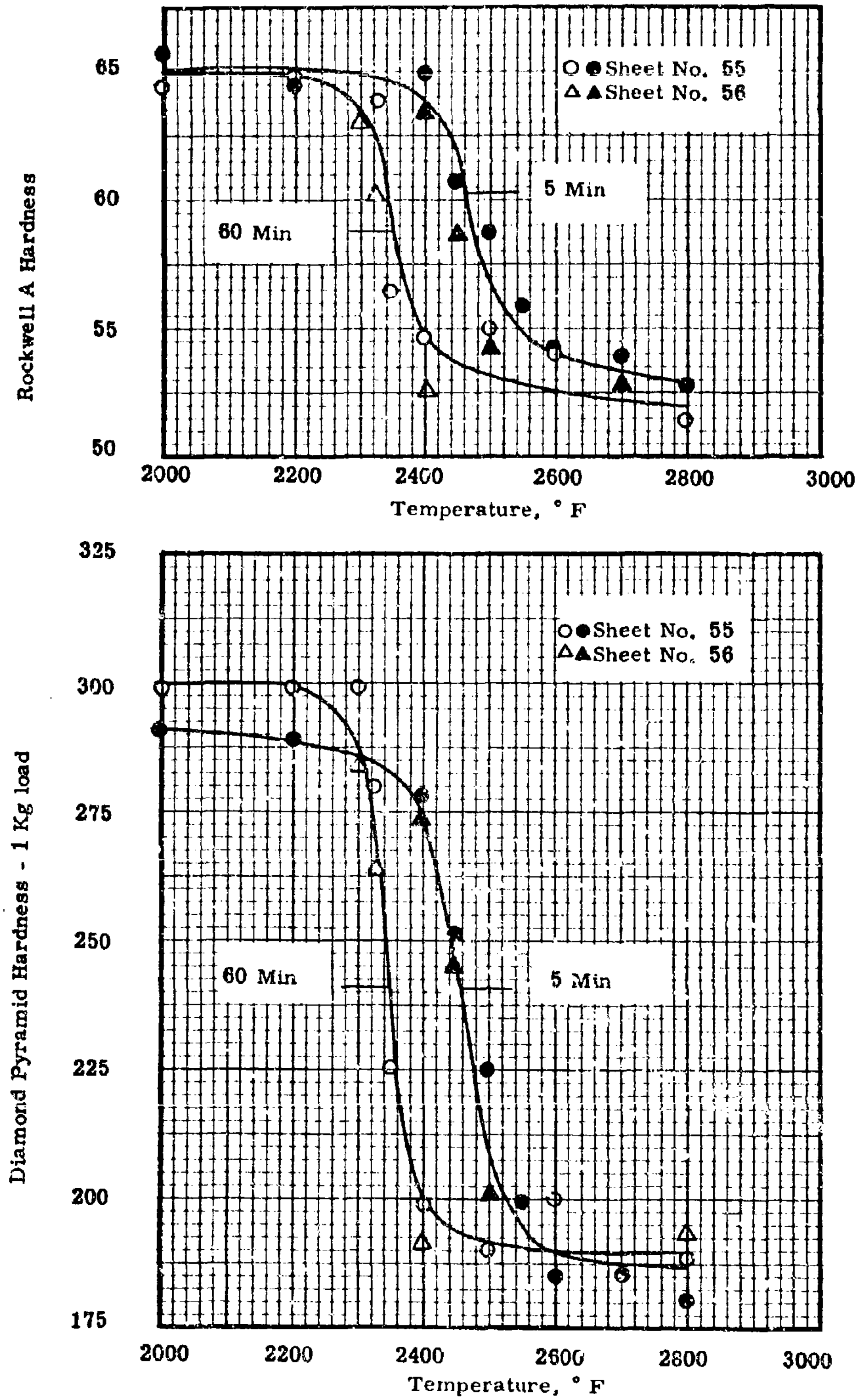
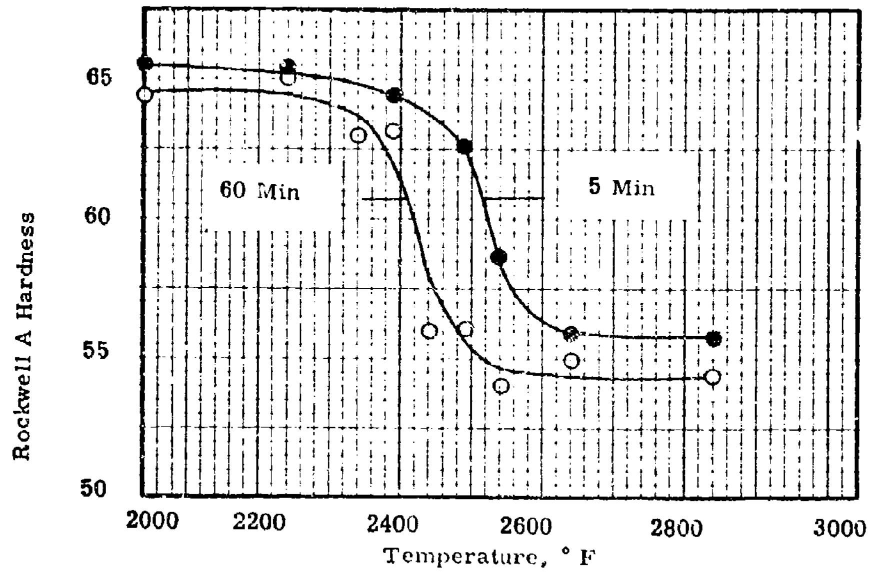


Figure 42. The effect of temperature and time at temperature on the surface hardness and the cross-section hardness of 0.040-in. TZM sheet. Each data point represents the average of five readings.



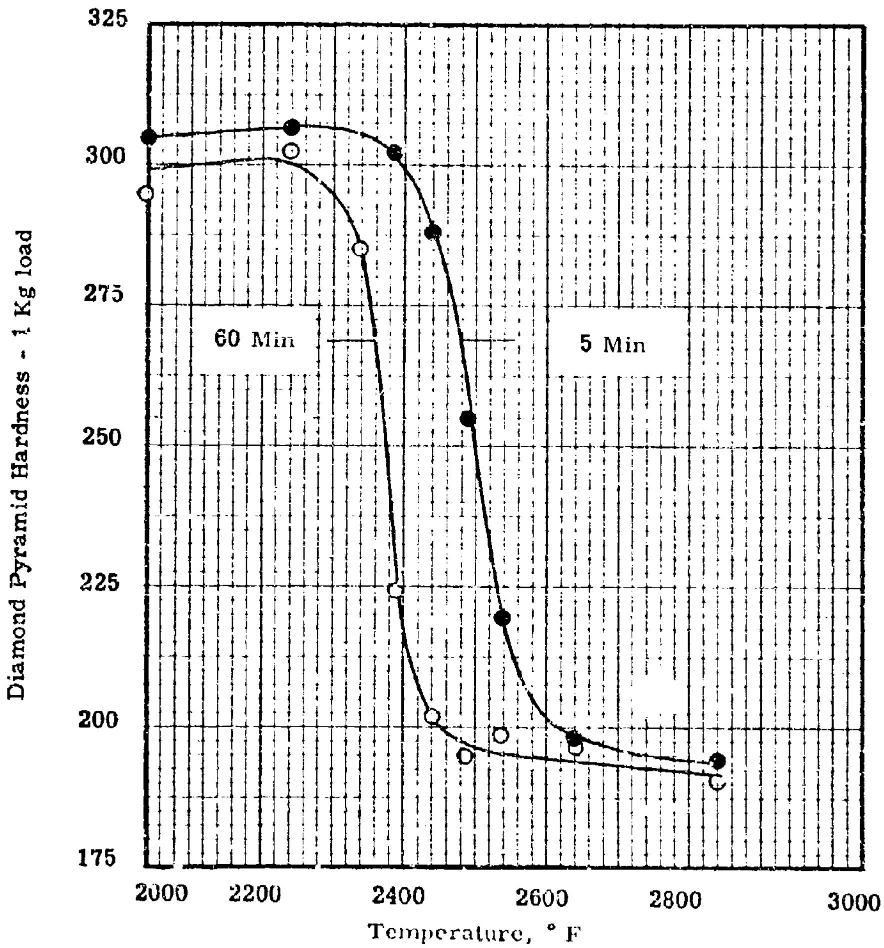


Figure 43. The effect of temperature and time at temperature on the surface hardness and cross-section hardness of 0.060-in. TZM sheet. Each data point shown represents the average of five readings.

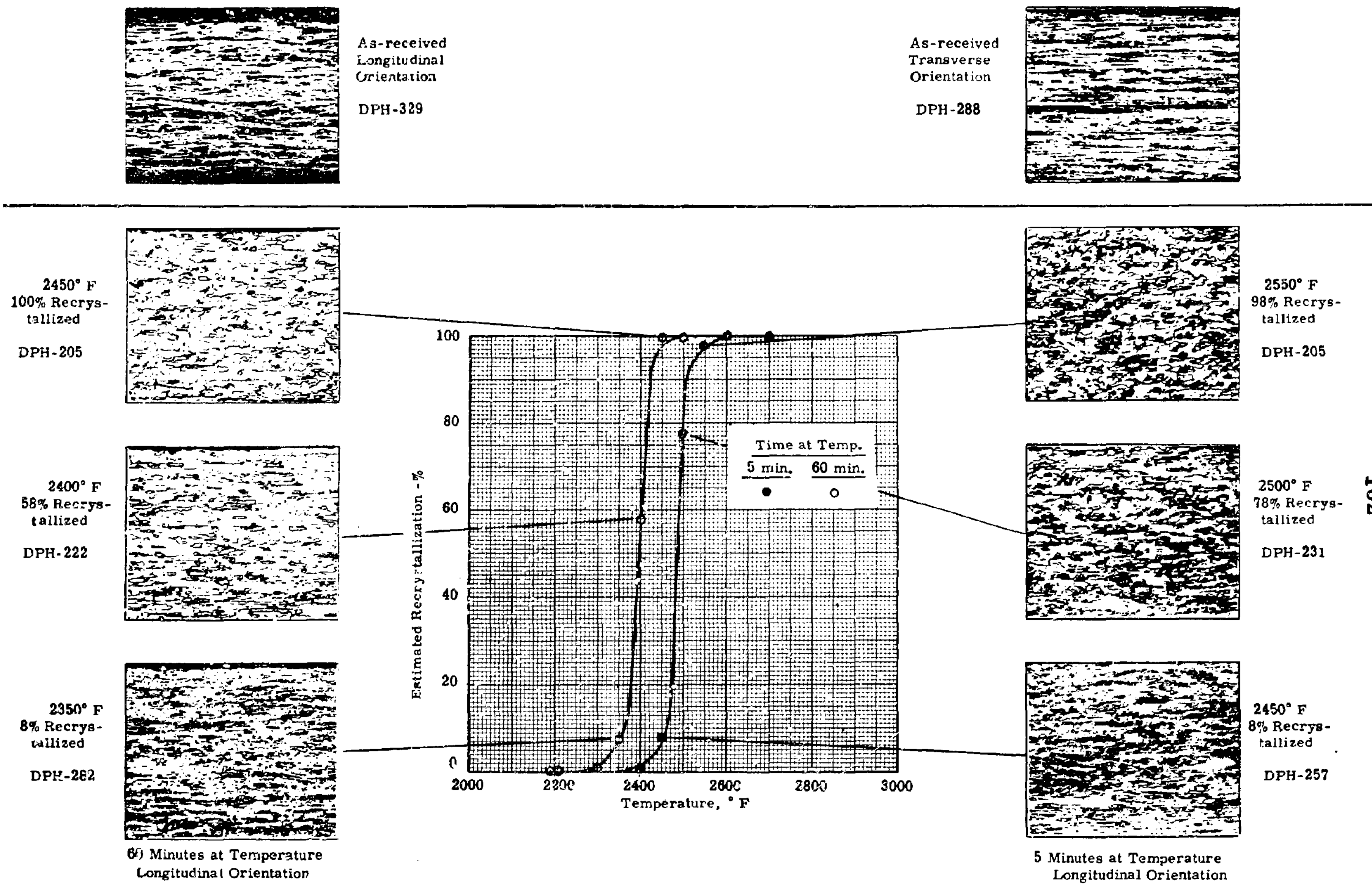


Figure 44. The effect of temperature and time at temperature on the recrystallization of 0.020-in. TZM sheet.
Photomicrographs - 100X; Etchant - Basic $K_3Fe(CN)_6$.

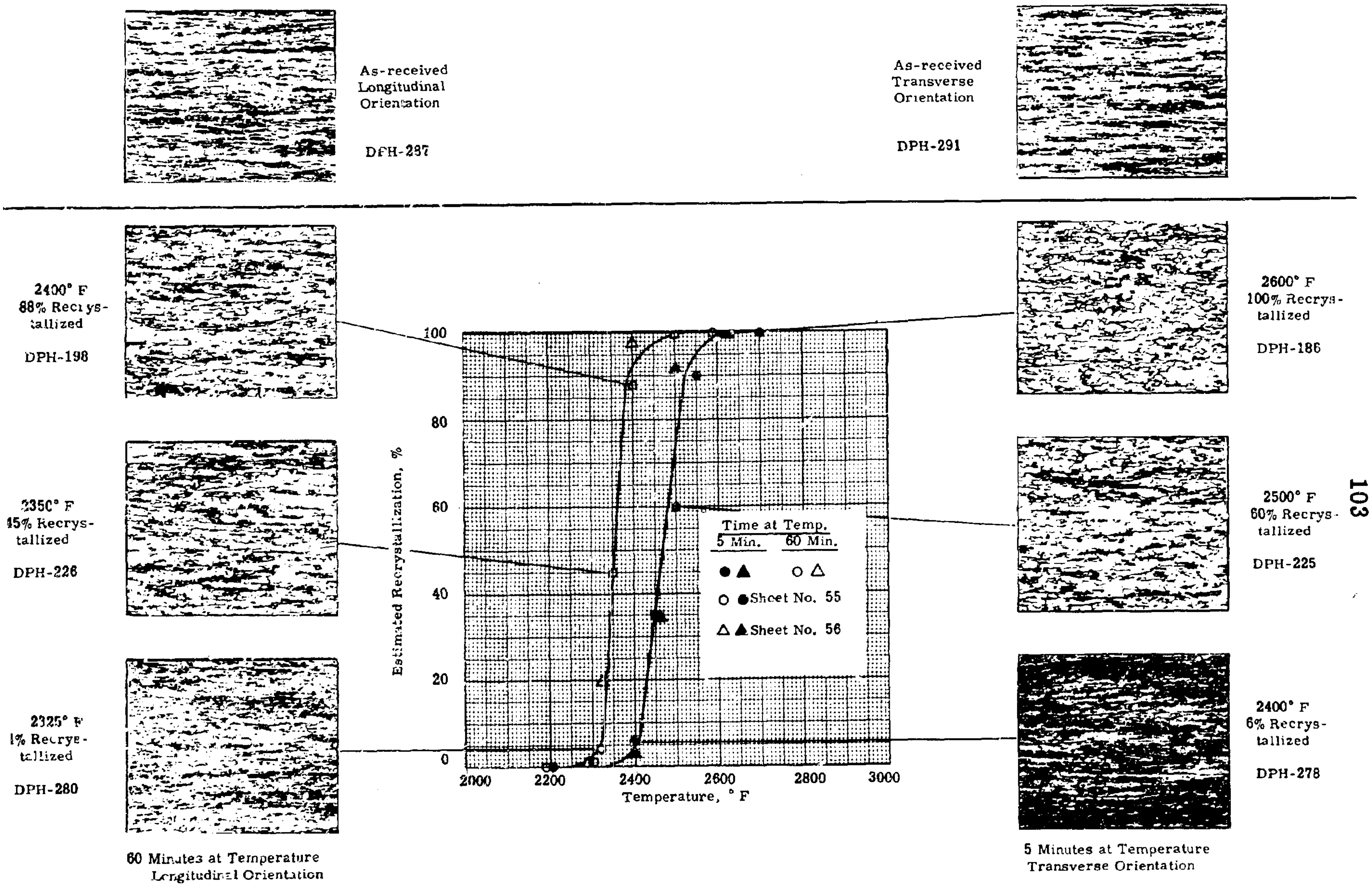


Figure 45. The effect of temperature and time at temperature on the recrystallization of 0.040-in. TZM sheet.
Photomicrographs (Sheet 55 only) 100X; Etchant - Basic $K_3Fe(CN)_6$.

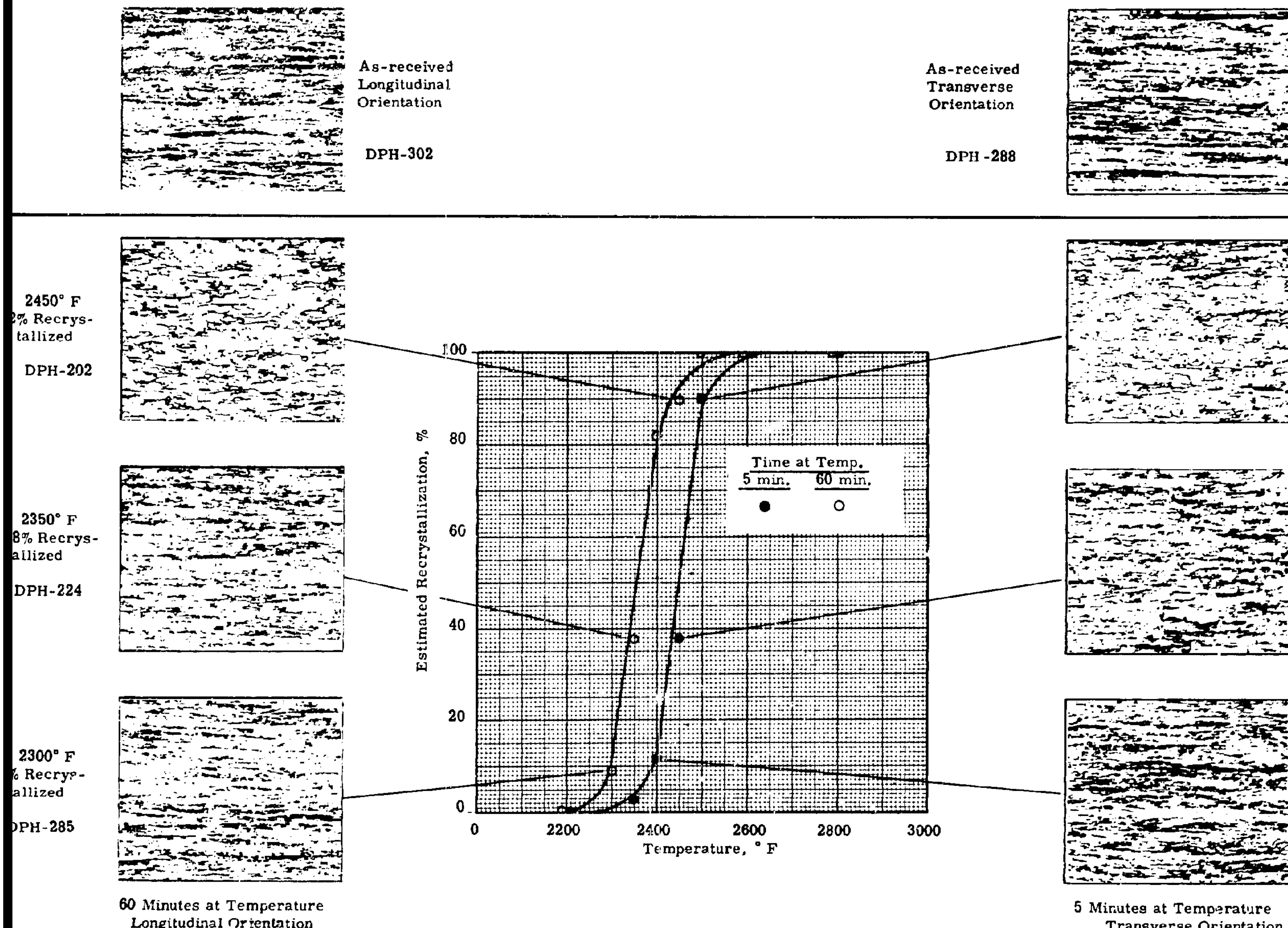


Figure 46. The effect of temperature and time at temperature on the recrystallization of 0.060-in. TZM sheet.
Photomicrographs - 100X; Etchant - Basic $K_3Fe(CN)_6$.

The recrystallization temperature for each gage as determined by the two methods are in good agreement. As shown in the table, the recrystallization temperature of the 0.020-in. TZM sheet was approximately 40° F higher than that of the 0.040-in. and the 0.060-in. sheet.

Tensile-Uncoated Sheet

Data obtained from tensile evaluations of the TZM sheet are summarized in tables and figures as shown below:

Sheet Thickness, In.	Condition	Table No.	Figure No.
0.020	Optimum	XXXV	47,48,53
	Recrystallized	XXXVI	47,48,53
0.040	Optimum	XXXVII	49,50,53
	Recrystallized	XXXVIII	49,50,53
0.060	Optimum	XXXIX	51,52,53
	Recrystallized	XL	51,52,53

These results of tensile tests on the TZM sheet showed that the ultimate tensile strength of the three sheet thicknesses in the optimum condition decreased from approximately 135 ksi at 75° F to about 15 ksi at 3000° F. The room temperature transverse tensile strength was greater than the longitudinal tensile strength by about 8 ksi. Generally, the 0.2%-offset yield was about 85% of the ultimate tensile strength. In the recrystallized condition, the yield and tensile strengths of the TZM sheets are uniformly lower than in the optimum condition by approximately 35 to 40 ksi at temperatures up to 2200° F. The data for the 0.040-in. sheet in the optimum and recrystallized conditions (Figure 49) suggests that the material in the optimum condition retains a strength advantage over the recrystallized sheet up to 3000° F, even though recrystallization occurs below 2400° F. The ductility data for the three gages indicate that in the optimum condition a ductility minimum probably exists at about 2000° F for both elongation and reduction of area. Generally, the modulus of elasticity decreased with increasing temperature up to 3000° F, with no consistent difference in the moduli of the sheet in different thicknesses and structural conditions being apparent.

Table XXXV

Tensile Properties of 0.020-In. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
74-3	L	75	115.5	133.5	48	9	25
74-16	L	75	120.0	133.0	43	13	22
Average			117.8	133.3	46	11	24
74-22	T	75	136.8	141.0	51	9	22
74-24	T	75	139.0	141.0	46	8	18
Average			137.9	141.0	48	8	20
74-5	L	2000	70.0	80.8	40	4	8
74-6	L	2000	70.3	77.5	37	3	11
Average			70.2	79.2	38	4	10
74-8	L	2200	61.7	72.7	36	6	25
74-9	L	2200	59.2	71.8	40	5	13
Average			60.5	72.3	38	6	19
74-11	L	2500	36.1	42.4	26	9	20
74-12	L	2500	42.2	50.0	30	8	23
74-17	L	2500	52.2	63.2	40	5	28
Average			42.6	51.9	32	7	24
74-13	L	3000	8.2	13.7	14	53	>95
74-15	L	3000	8.4	14.4	17	40	>95
Average			8.3	14.1	16	46	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6 % offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table XXXVI

Tensile Properties of 0.020-In. TZM Sheet at Different Temperatures[1] in the Recrystallized Condition[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
74-1	L	75	80.3	105.5	48	14	23
74-4	L	75	80.8	107.0	53	18	22
Average			80.6	106.3	50	16	22
74-21	T	75	85.5	108.5	53	18	19
74-23	T	75	83.5	108.3	53	16	19
Average			84.5	108.4	53	17	19
74-7	L	2200	27.3	32.0	29	6	25
74-10	L	2200	24.8	32.3	29	3	30
Average			26.1	32.2	29	4	28

1 Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75° F the strain rate was 0.005 min^{-1} to 0.6% offset and 0.05 min^{-1} from 0.6% offset to fracture. At 2200° F the strain rate was 0.05 min^{-1} to fracture.

2 Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

Table XXXVII

Tensile Properties of 0.040-In. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
55-27	L	75	109.0	129.0	46	28	46
55-3	L	75	105.8	129.7	49	16	34
56-27	L	75	119.2	129.0	54	24	38
56-3	L	75	116.0	140.1	46	18	34
Average			112.5	132.0	49	21	38
55-92	T	75	134.0	140.0	48	13	38
56-92	T	75	130.0	137.0	51	16	38
Average			132.0	138.5	49	14	38
55-7	L	1200	66.6	92.6	48	7	38
56-7	L	1200	80.6	92.0	28	10	33
Average			73.6	92.3	38	8	36
55-11	L	2000	72.0	78.5	29	6	36
56-11	L	2000	69.0	78.0	30	5	26
Average			70.5	78.3	30	6	31
55-15	L	2200	58.7	71.8	31	9	36
56-15	L	2200	61.2	72.5	31	7	18
Average			60.0	72.2	31	8	27
55-19	L	2500	31.8	38.8	20	12	>95
56-19	L	2500	39.1	44.7	23	8	73
Average			35.5	41.7	22	10	>84
55-23	L	3000	7.7	13.4	14	54	>95
56-23	L	3000	8.7	14.5	12	58	>95
Average			8.2	14.0	13	56	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table XXXVIII

Tensile Properties of 0.040-In. TZM Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
55-4	L	75	71.2	93.8	54	21	23
56-4	L	75	73.7	97.3	45	12	12
Average			72.5	95.6	49	16	18
55-89	T	75	75.5	96.3	44	15	12
56-89	T	75	75.5	93.0	46	10	17
Average			75.5	94.7	45	12	14
55-31	L	1200	21.5	48.8	29	16	51
56-8	L	1200	23.7	55.3	38	18	52
Average			22.6	52.1	34	17	52
55-13	L	2000	20.3	40.2	29	14	47
56-13	L	2000	22.2	37.1	30	14	58
Average			21.3	38.7	30	14	52
55-17	L	2200	18.2	28.3	36	24	45
56-17	L	2200	20.5	32.3	35	19	47
Average			19.4	30.3	36	22	46
55-22	L	2500	15.4	23.5	24	27	60
55-22	L	2500	14.[illegible]	22.4	2[illegible]	27	51
Average			15.1	23.0	24	27	56
55-26	L	3000	11.7	14.1	15	42	63
56-26	L	3000	11.2	15.4	18	50	64
Average			11.5	14.8	16	46	64

[1] Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

Table XXXIX

Tensile Properties of 0.060-In. TZM Sheet in the Optimum Condition[1] at Different Temperatures[2]

Specimen Number	Orien-tation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
23-17	L	75	117.0	134.0	46	20	40
23-2	L	75	98.0	132.5	47	-[3]	-[3]
23-3	L	75	109.5	134.0	42	22	44
Average			108.2	133.5	44	21	42
23-22	T	75	128.0	141.5	46	6	44
23-24	T	75	131.0	140.5	47	4	4
Average			129.5	141.0	46	5	24
23-5	L	2000	81.8	85.5	29	5	24
23-6	L	2000	85.5	90.7	30	7	19
Average			83.7	88.1	30	6	22
23-8	L	2200	67.5	74.2	29	10	25
23-9	L	2200	62.5	74.5	27	8	37
Average			65.0	74.4	28	9	31
23-11	L	2500	31.7	37.6	23	16	>95
23-12	L	2500	38.4	42.7	23	14	>95
Average			35.1	40.2	23	15	>95
23-13	L	3000	9.8	15.4	15	58	>95
23-15	L	3000	8.7	13.2	15	45	>95
Average			9.3	14.3	15	52	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6 % offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Fractured outside the gage length.

Table X L

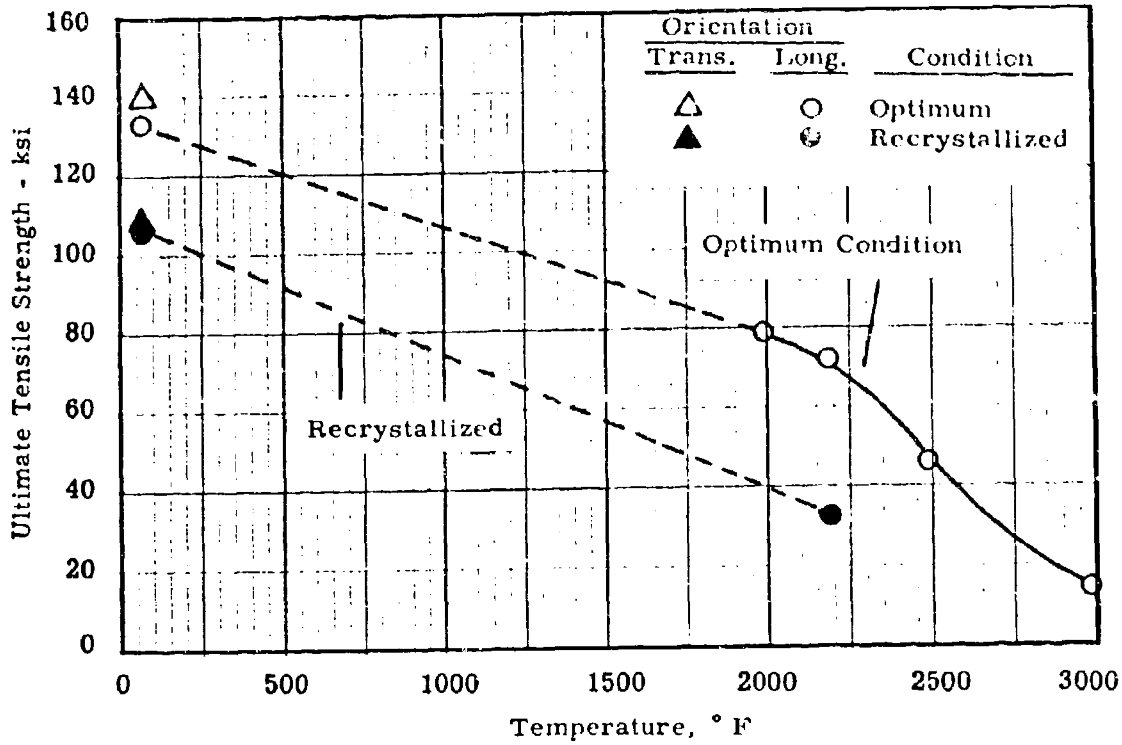
Tensile Properties of 0.060-In. TZM Sheet in the Recrystallized Condition[1] at Different Temperatures[2]

Specimen Number	Orientation	Temp °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elong. in 1 in. %	Reduction of Area %
23-1	L	75	81.7	100.2	49	20	20
23-4	L	75	79.8	99.5	47	18	14
Average			80.8	99.9	48	19	17
23-21	T	75	76.4	96.0	-[3]	26	24
23-23	T	75	77.8	96.0	47	23	28
Average			77.1	96.0	47	24	26
23-7	L	2200	21.4	29.7	27	26	56
23-10	L	2200	21.1	31.9	28	22	57
Average			21.2	30.8	28	24	56

1 Specimens were recrystallized at 2475° F in one hour in a vacuum of approximately 10^{-4} torr.

2 Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

3 Value calculated from stress-strain curve was abnormally high and was omitted from the table.



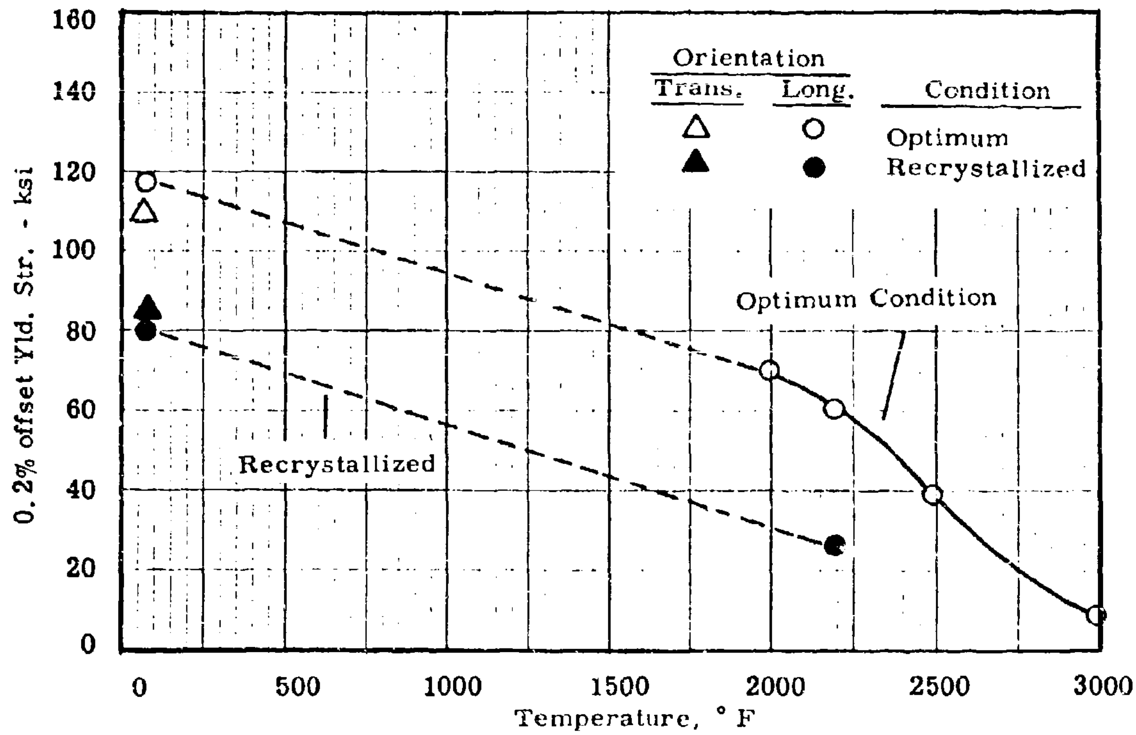


Figure 47. The ultimate-tensile and 0.2%-offset-yield strengths of 0.020-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

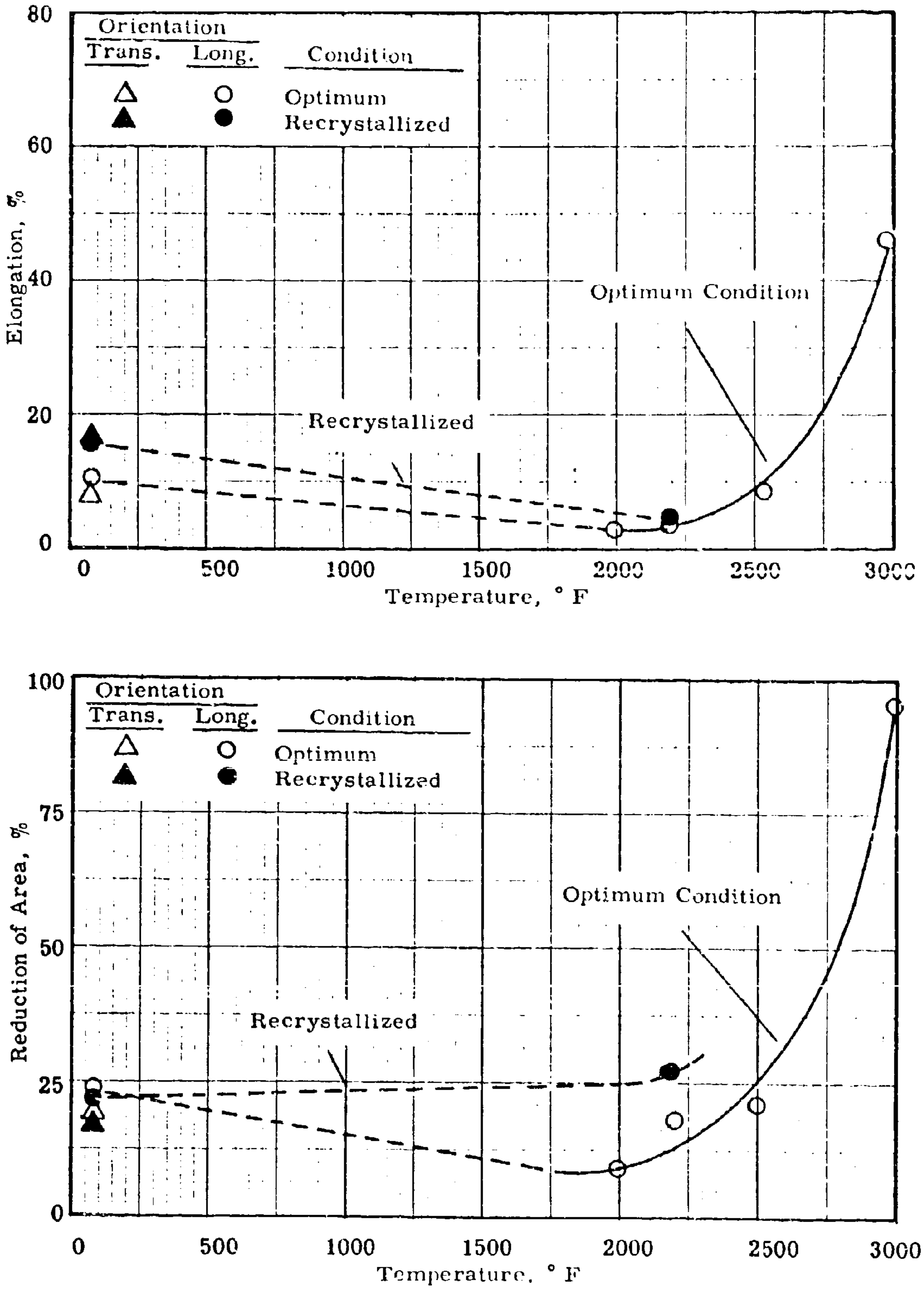


Figure 48. The percent elongation and reduction of area of 0.020-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

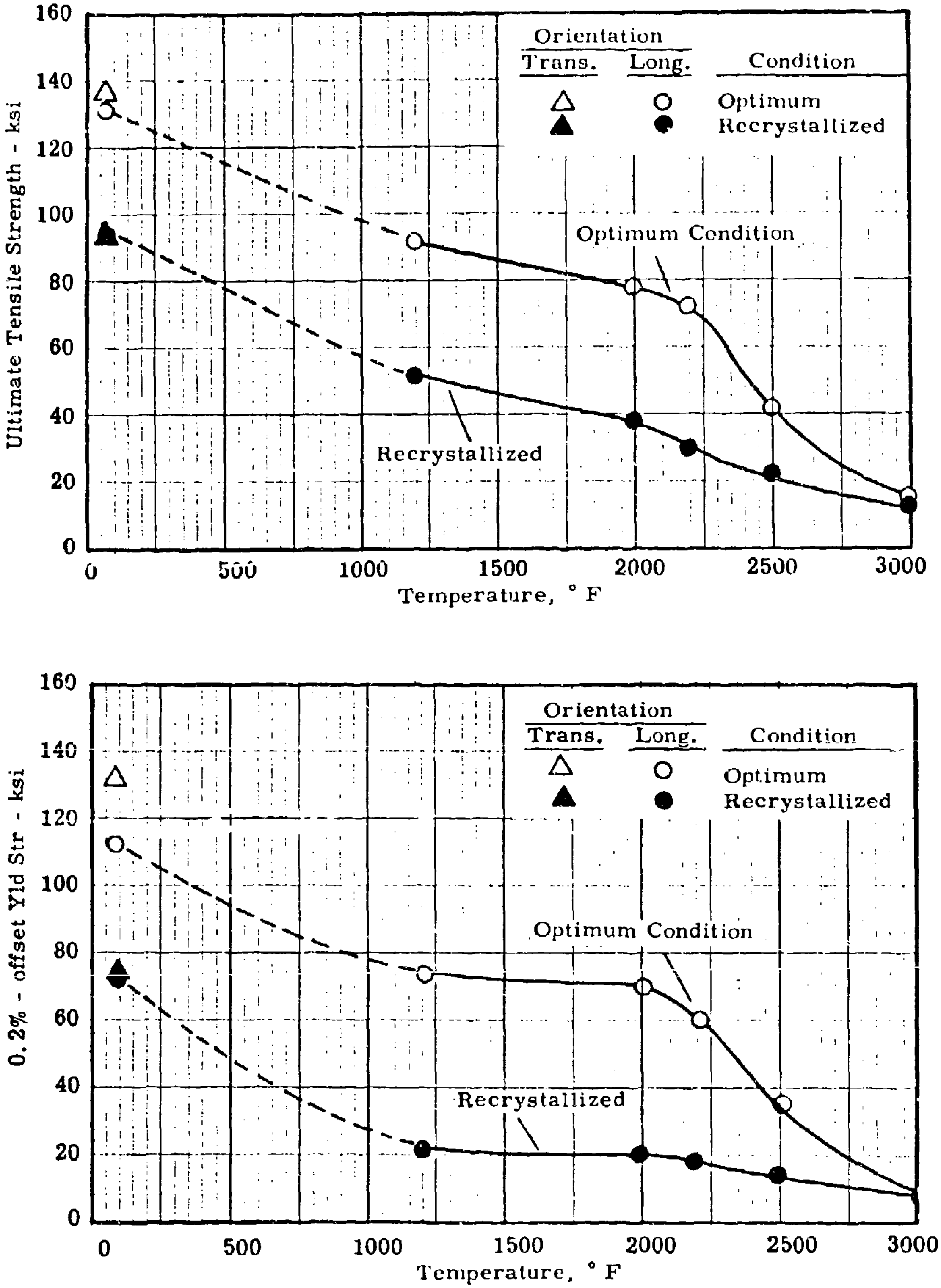


Figure 49. The ultimate-tensile and 0.2%-offset-yield strengths of 0.040-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

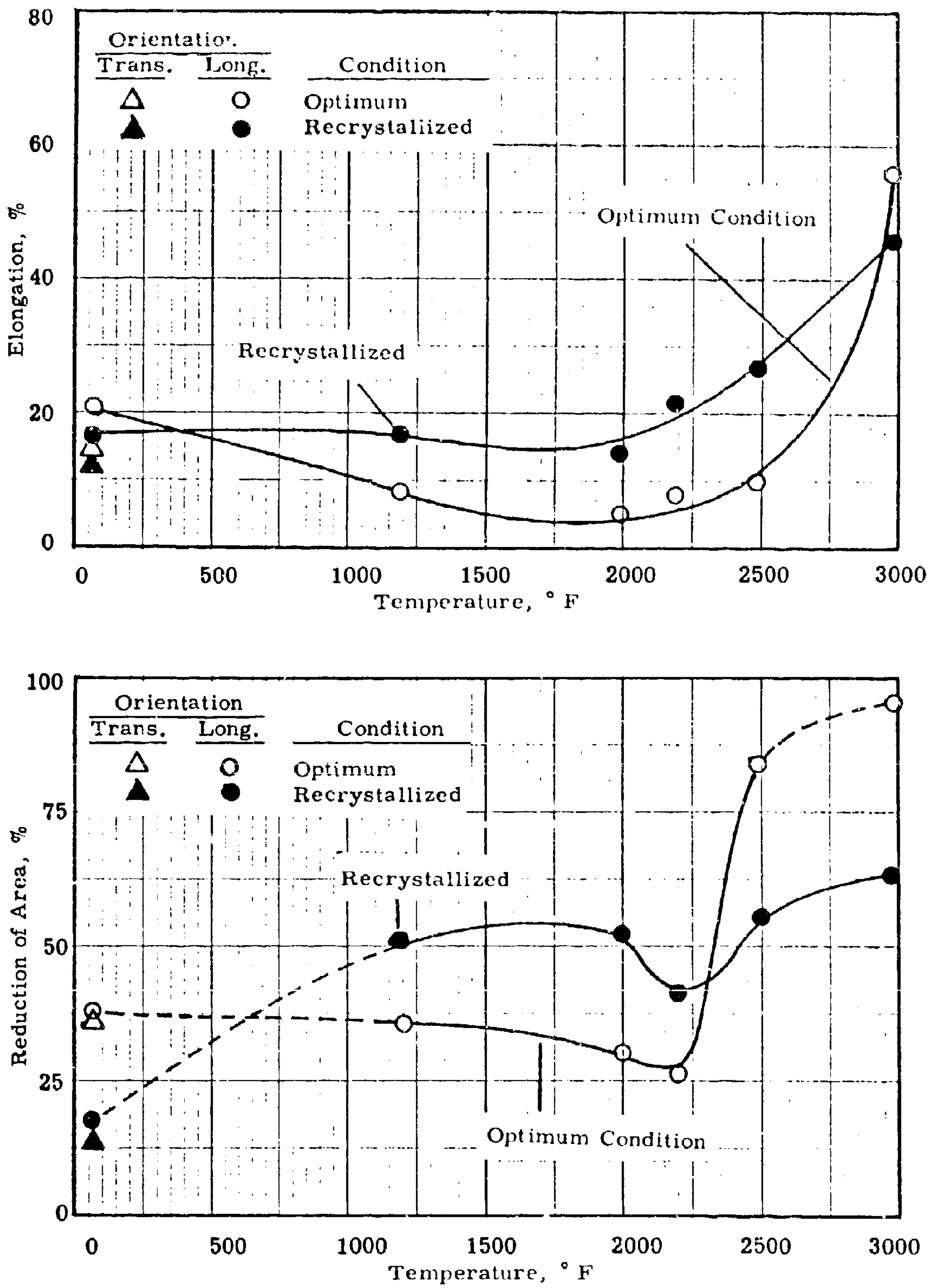
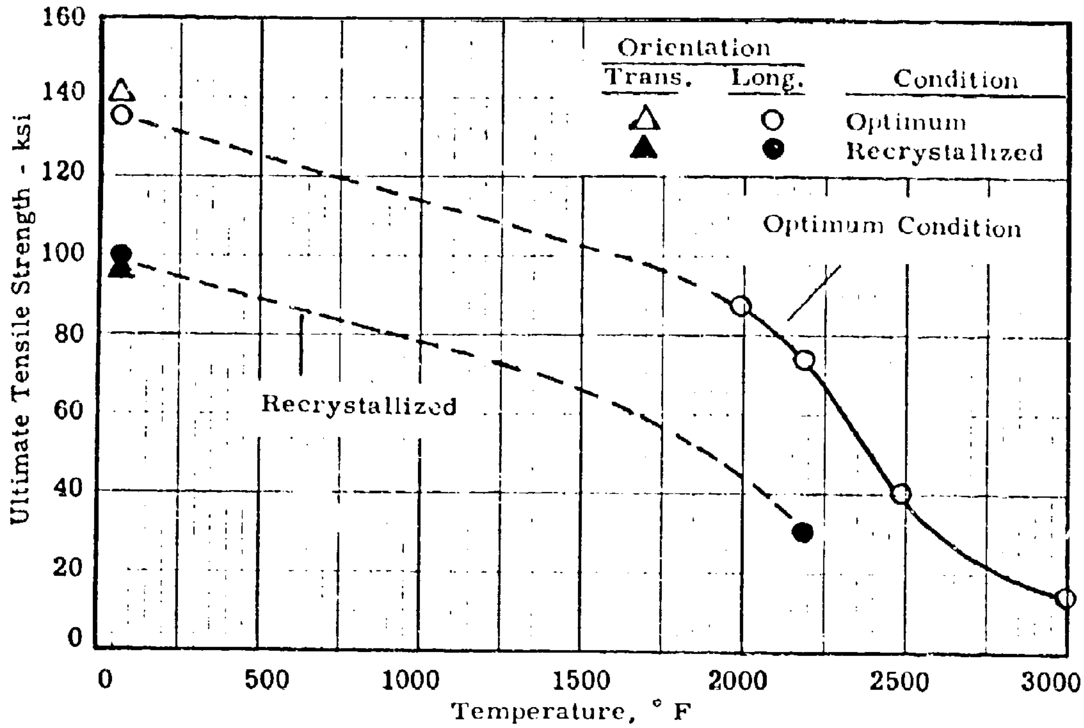


Figure 50. The percent elongation and reduction of area of 0.040-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.



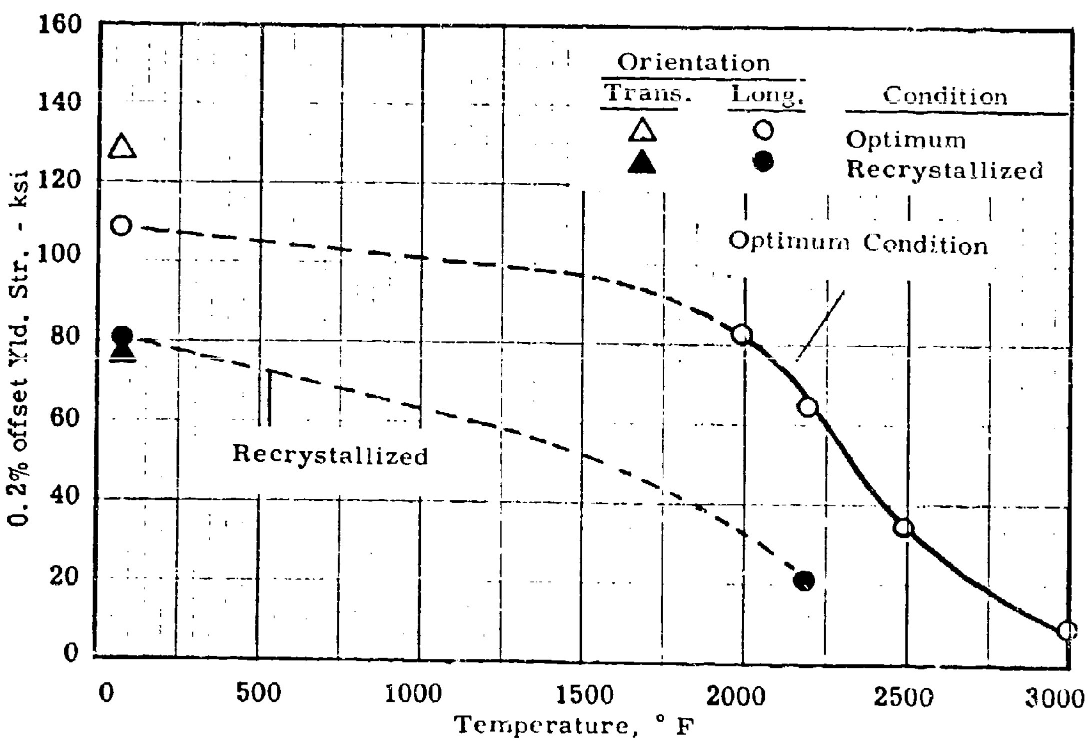
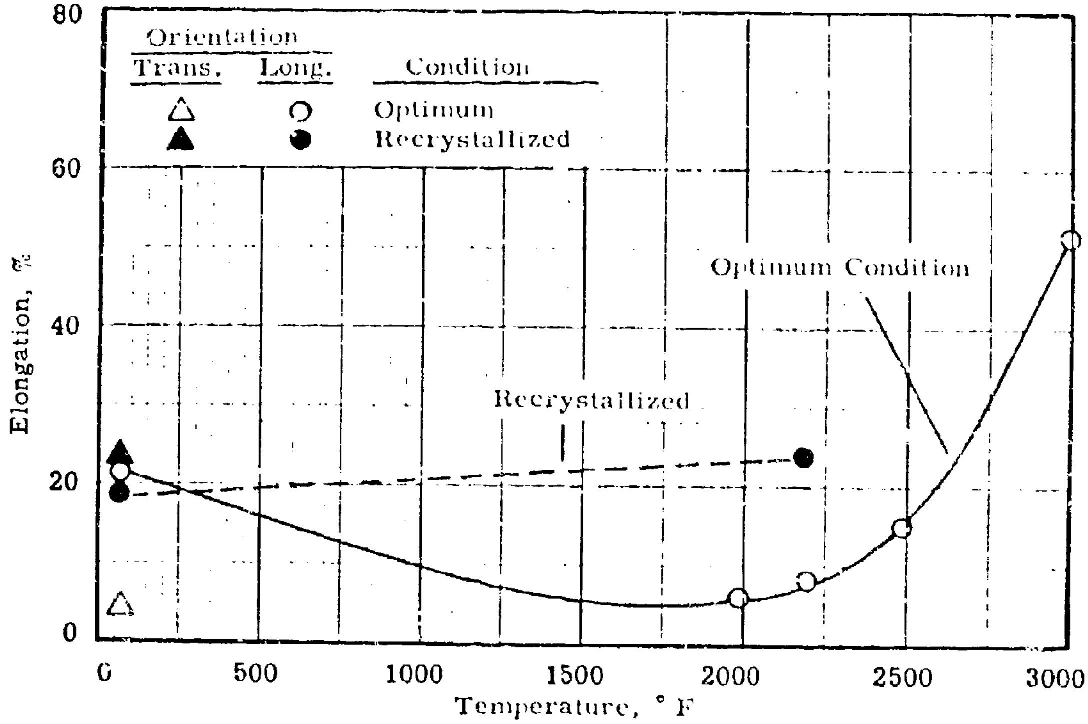


Figure 51. The ultimate tensile and 0.2%-offset-yield strengths of 0.060-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.



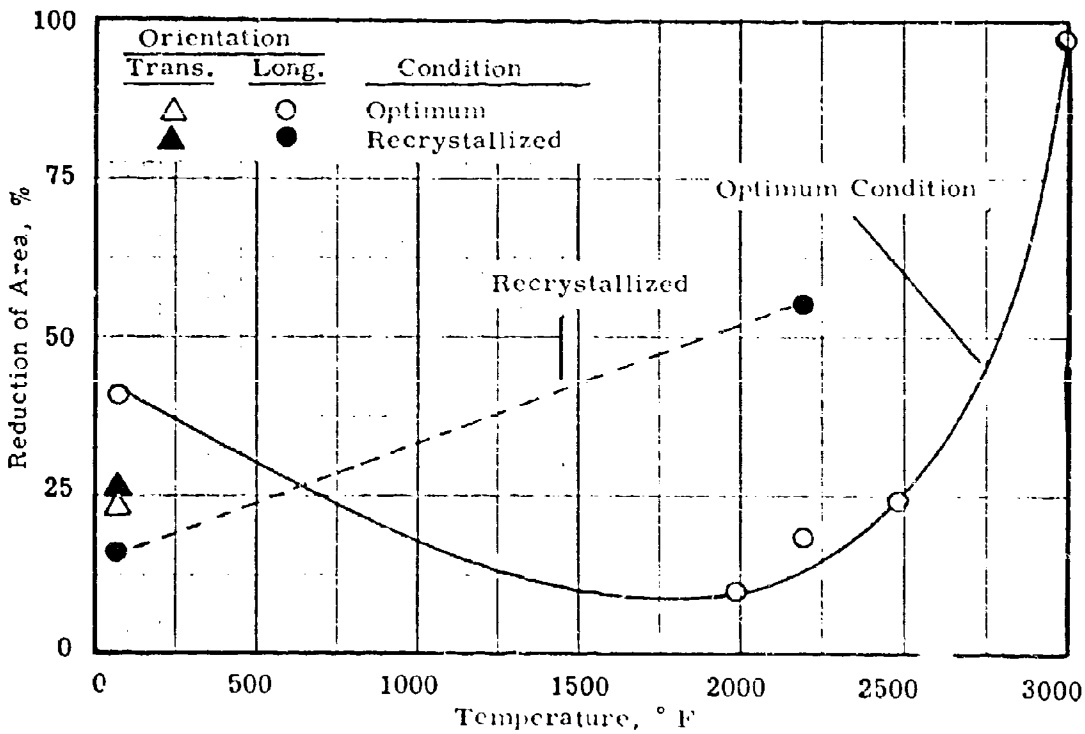


Figure 52. Percent elongation and reduction of area of 0.060-in. TZM sheet in the optimum and recrystallized conditions at different temperatures.

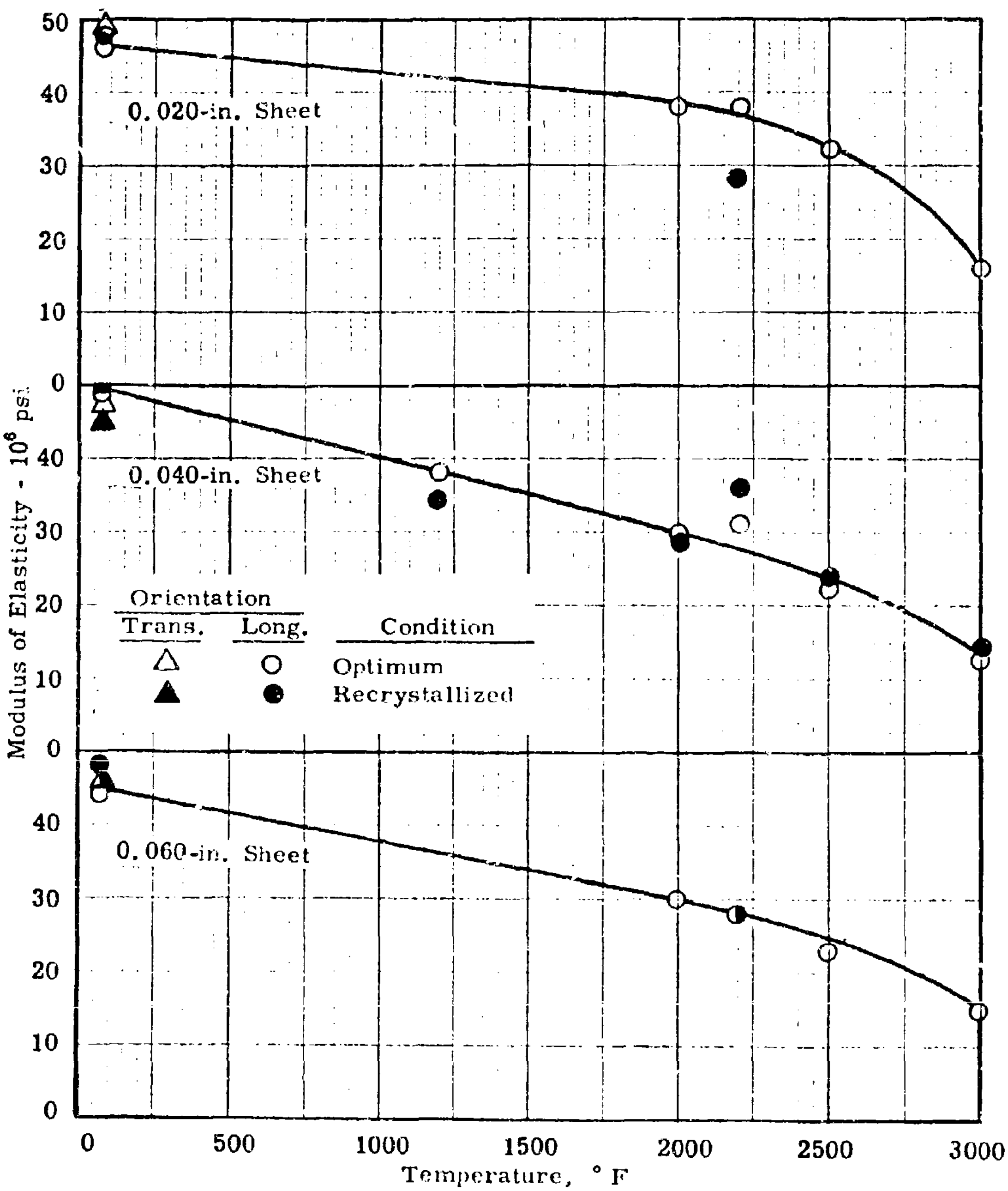


Figure 53. Modulus of elasticity of TZM sheet in the optimum and recrystallized conditions at different temperatures.

Table XLI shows a comparison of some of the data developed at SRI with similar averaged data obtained by Universal Cyclops on the TZM sheet. In general, the SRI and Universal Cyclops data are in good agreement, although the strength properties obtained by SRI seem to be slightly higher than averaged data obtained by Universal Cyclops.

Tensile - Coated Sheet

The tensile properties obtained from evaluation of the coated 0.040-in. TZM sheet in the optimum condition are summarized in Tables XLII and XLIII for the W-3 and PFR-6 coatings, respectively. These properties are plotted as functions of temperature in Figures 54 through 56. The data shown in these tables and figures were based on the cross sectional area of the specimens before the coatings were applied. The application of coatings to the TZM sheet had a significant effect on the tensile properties. In general, the strength and modulus of elasticity were substantially lower than the normal uncoated TZM sheet at comparable temperatures. For example, the tensile strength of the uncoated sheet in the longitudinal direction was about 135 ksi at room temperature, whereas after application of the W-3 and PFR-6 coatings it was 103 ksi and 77 ksi, respectively. Like the uncoated sheet, the strength properties of the coated TZM were slightly higher in the transverse direction than in the longitudinal direction. At 2500° F the strength of the W-3 coated sheet was slightly higher than the uncoated sheet. The ductility (both elongation and reduction of area) of the sheet at room temperature was adversely affected by both coatings in the longitudinal direction but not in the transverse direction. At elevated temperatures, the ductility of the coated and uncoated sheet was generally comparable except at 2000 and 2200° F, where the percent reduction of area for the coated sheet was considerably higher than for the uncoated sheet.

Application of the PFR-6 coating to the TZM sheet reduced the strength properties and moduli of the base material significantly more than the application of the W-3 coating (Figures 54 and 56). Generally, the ductility of W-3 and PFR-6 coated sheet was comparable over the temperature range evaluated (Figure 55).

Notched Tensile Properties

Data from evaluation of notched and unnotched tensile specimens to determine the brittle-ductile transition temperature of the 0.040-in. TZM sheet in the optimum and recrystallized conditions are summarized in Tables XLIV and XLV and Figures 57 and 58, respectively. The temperature range of the

Table XLI

Comparison of Tensile Data for TZM Sheet in the Optimum Condition from Universal Cyclops and Southern Research Institute

Sheet Thickness In.	Property[1]	Universal Cyclops 75° F Long.	Universal Cyclops 75° F Trans.	Universal Cyclops 2000° F Trans.	Southern Research Institute 75° F Long.	Southern Research Institute 75° F Trans.	Southern Research Institute 2000° F Long.
	UTS	129	137	82	133	141	79
0.020	0.2% Y.S.	112	128	76	118	138	70
	%E	12	9	4	11	8	4
	UTS	129	134	82	132	138	78
0.040	0.2%Y.S.	109	128	78	112	132	70
	%E	15	9	5	21	14	6
	UTS	129	135	83	133	141	88
0.060	0.2%Y.S.	112	128	80	108	129	84
	%E	17	13	7	21	5	6

[1] Strength properties are in units of 1000 psi.

Table XLII

Tensile Properties of W-3 Coated 0.040-In. TZM Sheet in the Optimum Condition at Different Temperatures[1,2,3]

Specimen Number	Orientation	Temp. °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elongation in./in. %	Reduction of Area %
55-37	L	75	95.5	102.6	37	1	0
56-14	L	75	95.8	104.7	40	2	0
Average			95.6	103.6	38	2	0
55-94	T	75	128.7	136.6	41	12	36
56-94	T	75	108.9	115.5	39	10	39
Average			118.8	126.1	40	11	38
55-9	L	1200	68.0	72.2	24	6	35
56-9	L	1200	71.1	78.4	34	6	36
Average			69.[illegible]	75.3	29	6	35
55-53	L	2000	59.4	63.8	22	6	>95
56-46	L	2000	62.5	65.4	24	10	>95
Average			61.0	64.6	23	8	>95
55-50	L	2200	57.8	60.9	15	7	>95
56-36	L	2200	55.2	57.8	20	10	>95
Average			56.5	59.4	18	9	>95
55-48	L	2500	48.2	51.3	15	10	>95
56-37	L	2500	43.6	47.5	19	10	>95
Average			45.9	49.4	17	10	>95
55-38	L	3000	7.2	11.3	12	39	>95
56-29	L	3000	7.4	12.0	11	54	>95
Average			7.3	11.6	12	47	>95

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

[2] Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200° F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000° F and above the strain rate was 0.05 min^{-1} to fracture.

[3] Calculations were based on area before coating.

Table XLIII

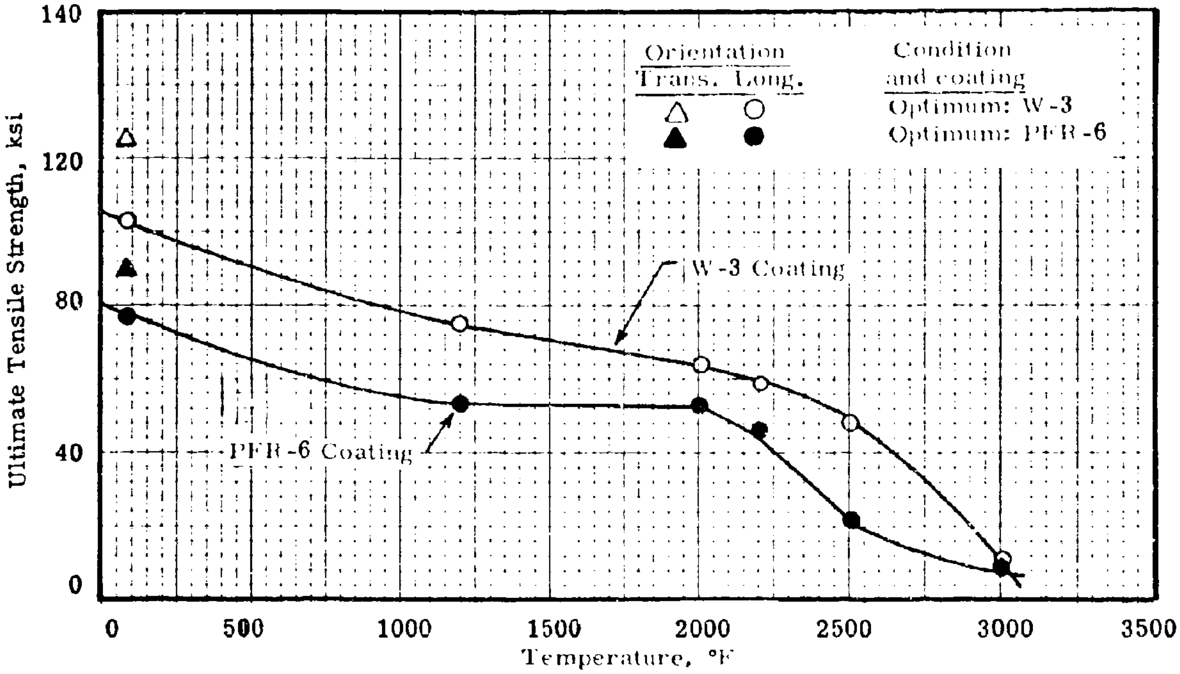
Tensile Properties of PFR-6 Coated 0.040-In. TZM Sheet In the Optimum Condition at Different Temperatures[1,2,3]

Specimen Number	Orientation	Temp. °F	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Mod. of Elasticity 10^6 psi	Elongation in. 1 in. %	Reduction of Area %
55-10	L	75	73.6	76.9	25	1	0
56-12	L	75	76.7	77.1	32	0.3	0
Average			75.2	77.0	28	0.7	0
55-93	T	75	84.6	90.0	30	9	40
56-91	T	75	86.6	91.9	30	8	49
Average			85.6	90.4	30	9	44
55-1	L	1200	47.0	48.0	21	5	34
56-1	L	1200	57.7	58.7	20	5	37
Average			52.3	53.4	21	5	36
55-29	L	2000	47.7	55.0	18	5	>95
56-28	L	2000	48.7	51.1	13	6	>95
Average			48.2	53.1	15	6	>95
55-21	L	2200	42.9	45.5	12	6	>95
56-38	L	2200	41.8	46.3	15	7	>95
Average			42.3	45.9	14	7	>95
55-46	L	2500	19.1	22.3	13	12	>95
56-50	L	2500	19.0	19.5	8	16	>95
Average			19.0	21.0	11	14	>95
55-42	L	3000	6.0	8.8	17	50	>95
56-42	L	3000	6.1	8.6	14	51	>95
Average			6.1	8.7	15	51	>95

[1]Sheet was hot-warm rolled and annealed for 1 hour at 2300°F.

[2]Specimens were heated by radiation in a vacuum of approximately 10^{-4} torr and held at temperature 15 min before straining. At 75 and 1200°F the strain rate to 0.6% offset was 0.005 min^{-1} and from 0.6% offset to fracture was 0.05 min^{-1}. At 2000°F and above the strain rate was 0.05 min^{-1} to fracture.

[3]Calculations based on cross section before coating.



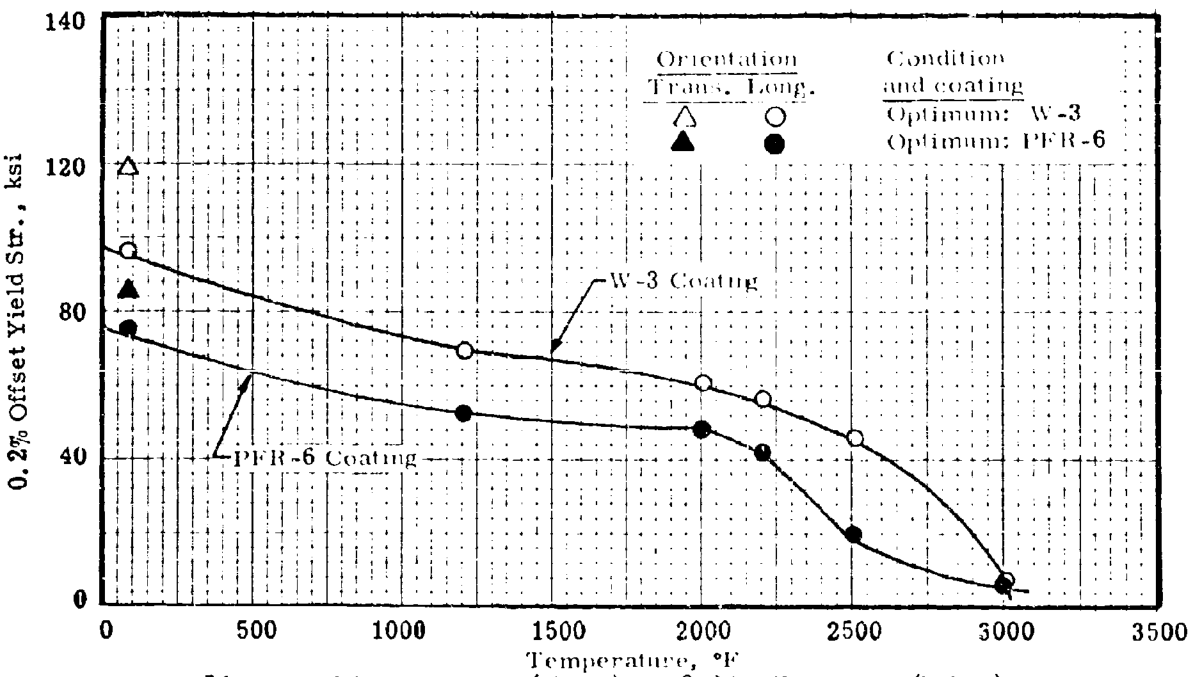
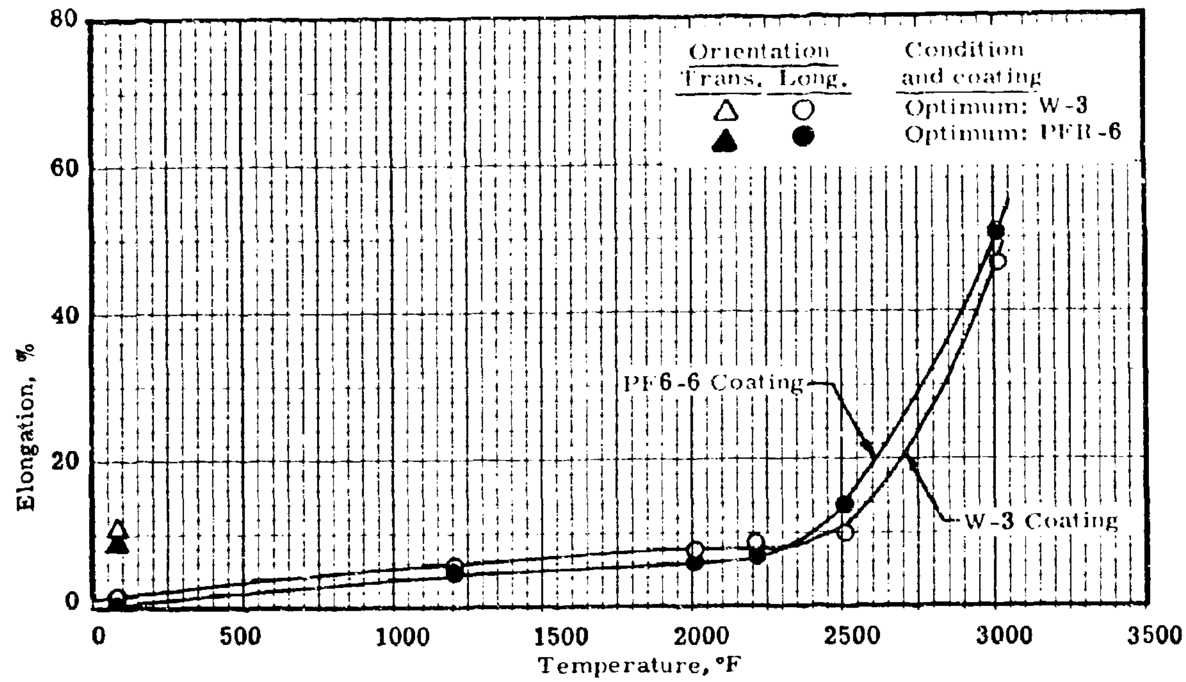


Figure 54. The ultimate-tensile (above) and 0.2%-offset-yield (below) strengths of coated 0.040-in. TZM sheet in the optimum condition at different temperatures



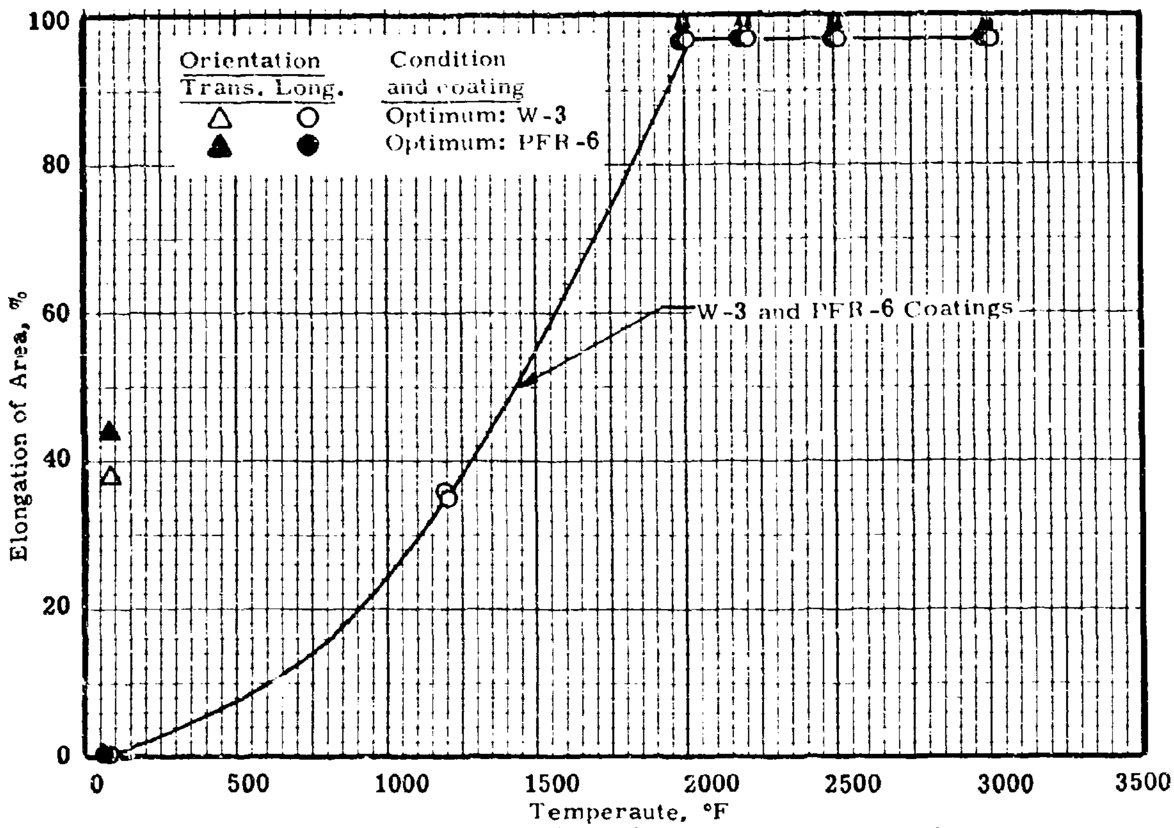


Figure 55. The present elongation (above) and reduction of area (below)of coated 0.040-in. TZM sheet in the optimum condition at different temperatures

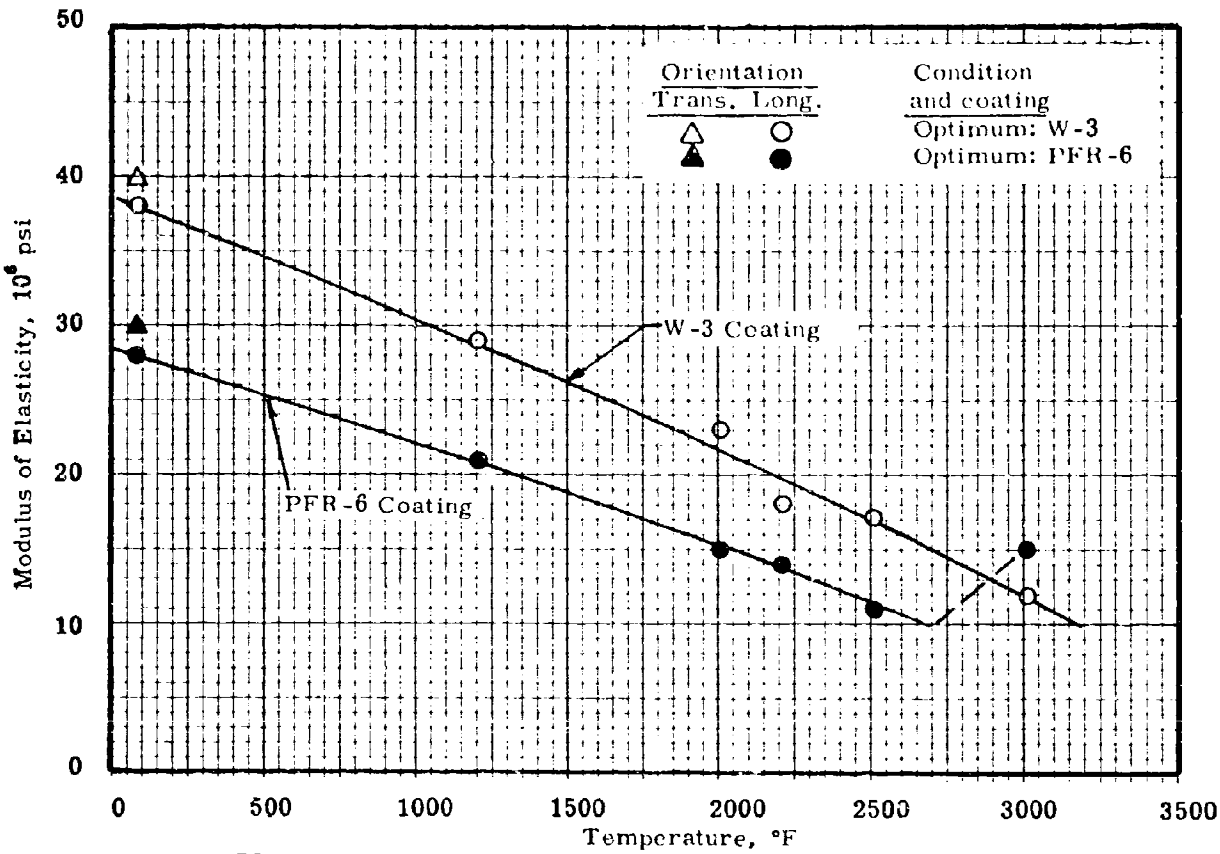


Figure 56. The modulus of elasticity of coated 0.040-in. TZM sheet in the optimum condition at different temperatures

Table XLIV

Notched-Tensile and Unnotched-Tensile Data for 0.040-in. TZM Sheet in the Optimum Condition[1] at Low Temperatures[2]

	Unnotched Specimens					Notched Specimens		
Temp °F	Specimen No.	0.2% Offset Yld. Str. ksi	Ultimate Tens. Str. ksi	Elong. in 1 in. %	Red. of Area %	Specimen No.	Ultimate Tens. Str. ksi	Notched/Unnotched Strength Ratio
75	55-27	109.0	129.0	28	46	55-61	142.8	
75	55-3	105.8	129.7	16	34	55-61	133.0	
75	56-27	119.2	129.0	24	38	-	-	
75	56-3	116.0	140.1	18	34	-	-	
	Average	112.5	132.0	21	38	Average	137.9	1.04
0	55-18	116.0	137.0	11	18	55-60	159.0	
0	56-18	119.0	140.0	12	41	56-60	159.0	
	Average	117.5	138.5	11.5	29.5	Average	159.0	1.14
-50	55-51	137.0	148.0	10	11	55-58	168.0	
-50	55-6	130.0	142.0	10	10	56-58	173.2	
	Average	133.5	145.0	10	10.5	Average	170.5	1.17
-100	55-2	144.0	158.0	8	37	55-56	188.0	
-100	56-2	153.0	160.0	8	40	56-56	182.0	
	Average	148.5	159.0	8	38.5	Average	185.0	1.16
-125	55-20	147.0	172.5	9	22	55-69	187.0	
-125	56-40	151.0	171.0	5	4	56-69	171.0	
	Average	149.0	171.7	7	13	Average	179.0	1.04
-150	55-32	166.5	176.0	4	9	55-65	187.0	
-150	56-32	163.0	170.0	5	18	56-67	195.0	
	Average	164.8	173.0	4.5	13.5	Average	191.0	1.10
-175	55-44	158.0	180.0	0	0	55-70	151.0	
-175	55-40	166.0	181.0	2	0	56-70	164.0	
	Average	162.0	180.5			Average	157.5	0.87
-200	55-33	173.0	184.0	0	0	55-63	153.0	
-200	-	-	-	-	-	56-63	153.0	
						Average	153.0	0.83

[1] Sheet was hot-warm rolled and annealed for 1 hour at 2300° F.

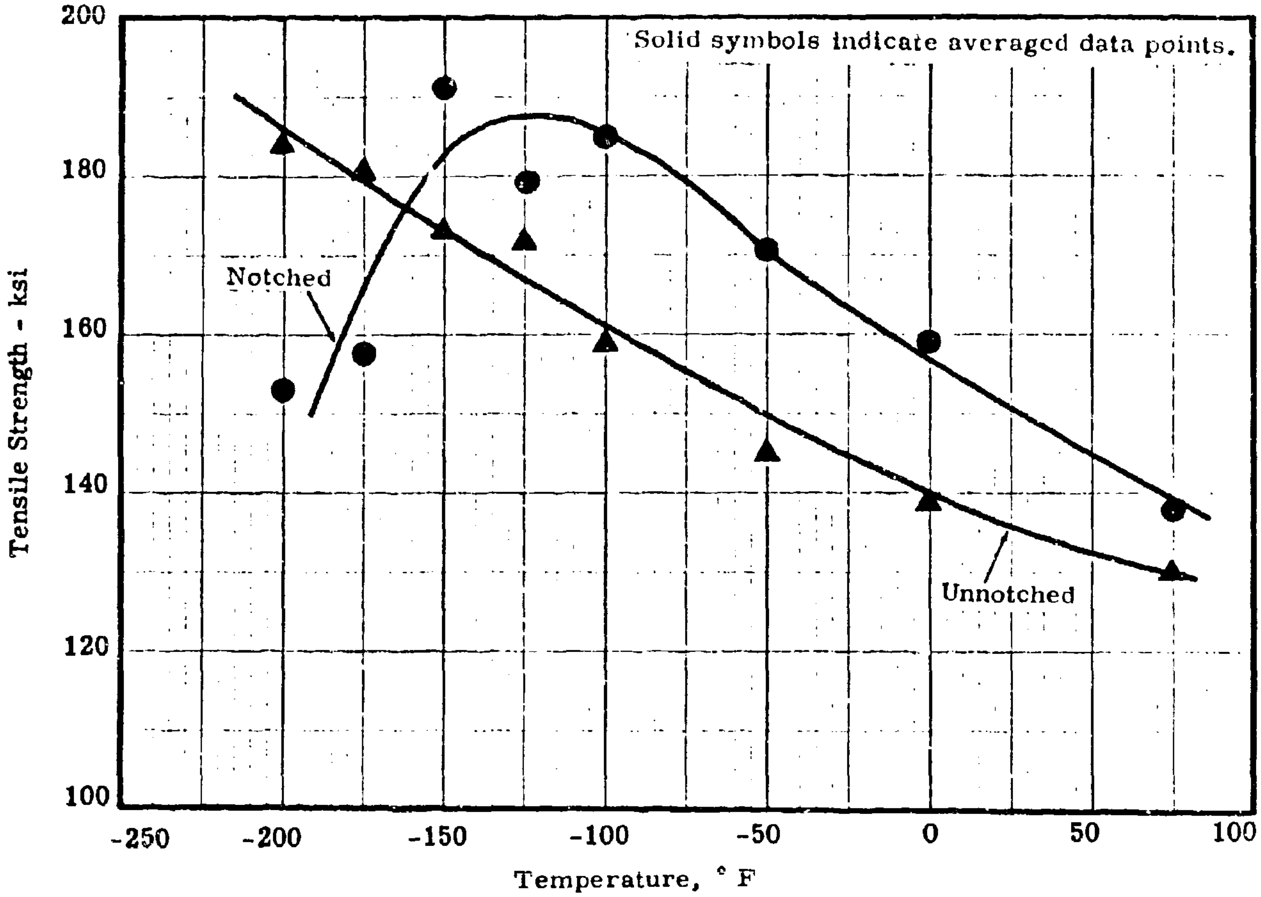
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min^{-1}.

Table XLV

Notched-Tensile and Unnotched-Tensile Data for 0.040-In. TZM Sheet in the Recrystallized Condition[1] at Low Temperatures[2]

	Unnotched Specimens					Notched Specimens		
Temp °F	Specimen No.	0.2% Offset Yld. Str. ksi	Ultimate Tens. Str. ksi	Elong. in 1 in. %	Red. of Area %	Specimen No.	Ultimate Tens. Str. ksi	Notched/Unnotched Strength Ratio
75	55-4	71.2	93.8	21	23	55-62	102.0	
75	56-4	73.7	97.3	12	12	56-62	96.6	
	Average	72.5	95.6	16	18	Average	99.3	1.03
0	55-54	88.0	89.0	0	0	55-59	118.5	
0	56-45	86.5	106.0	10	14	56-59	116.0	
	Average	87.2	97.5			Average	117.2	1.20
-50	55-41	105.0	108.0	3	0	55-57	138.0	
-50	56-43	101.0	101.0	0	0	56-57	133.6	
	Average	103.0	104.5			Average	135.8	1.29
-60	-	-	-	-	-	56-71	125.0	
-75	55-49	111.0	111.0	0	0	55-66	121.0	
-75	56-47	98.5	98.5	0	0	55-68	109.0	
-75	-	-	-	-	-	55-72	115.0	
-75	-	-	-	-	-	56-68	125.0	
	Average	104.7	105.0			Average	117.5	1.11
-85	-	-	-	-	-	55-71	135.0	
-100	55-52	89.0	89.0	0	0	56-55	141.5	
-100	56-41	119.0	133.0	9	13	56-66	141.3	
	Average	104.0	111.0			Average	141.4	1.27
-125	56-49	127.0	127.0	0	0	56-72	126.0	0.99
-150	55-47	132.0	134.0	0	0	55-64	53.1	
-150	56-52	132.0	138.0	0	0	56-64	89.3	
	Average	132.0	136.0			Average	71.2	0.52

[1] Specimens were recrystallized at 2475° F in one hour in a vacuum of 10^{-4} torr.
[2] Specimens were held approximately 15 min at temperature before straining to fracture at a strain rate of 0.005 min^{-1}.



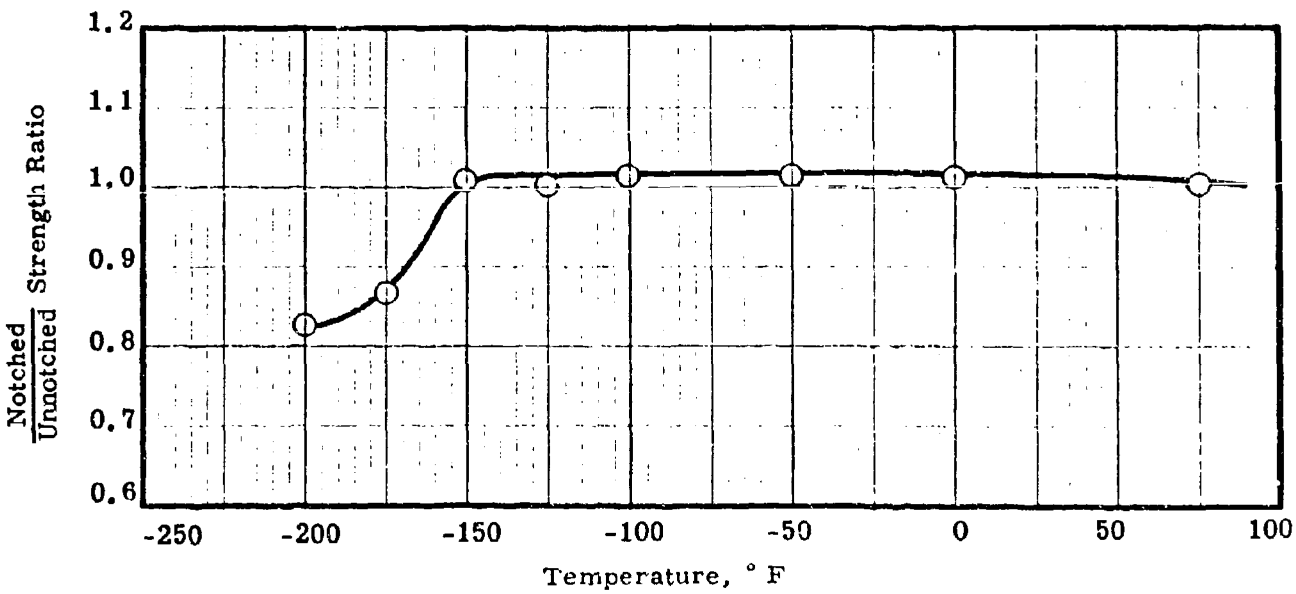
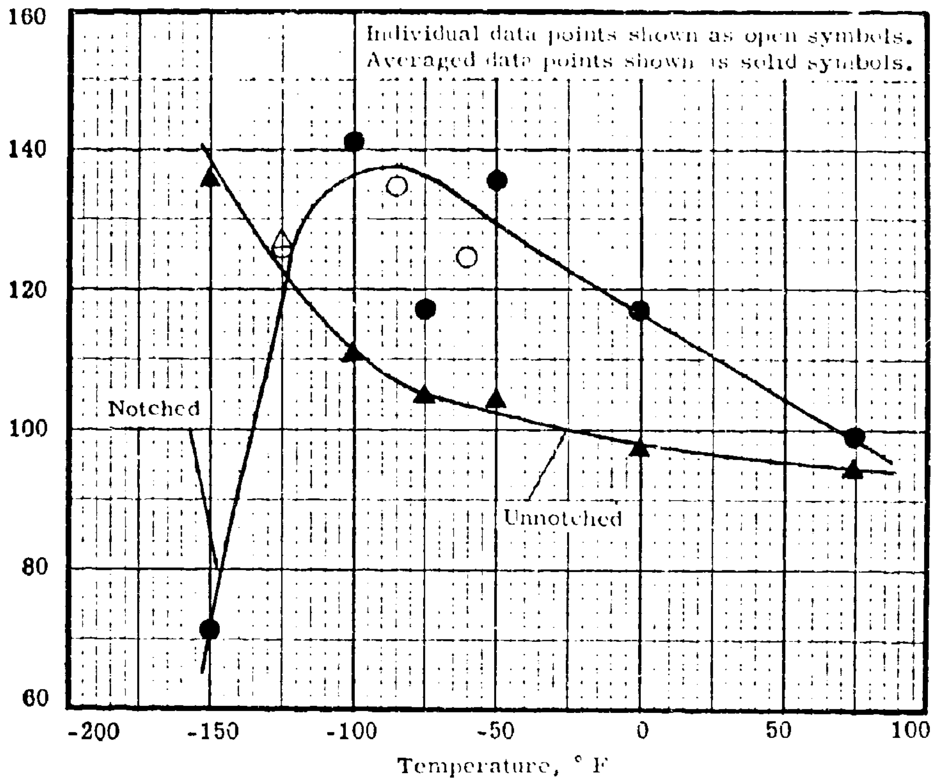


Figure 57. Notched and unnotched tensile strength and notched/unnotched tensile strength ratio at different temperatures for 0.040-in. TZM sheet in the optimum condition.



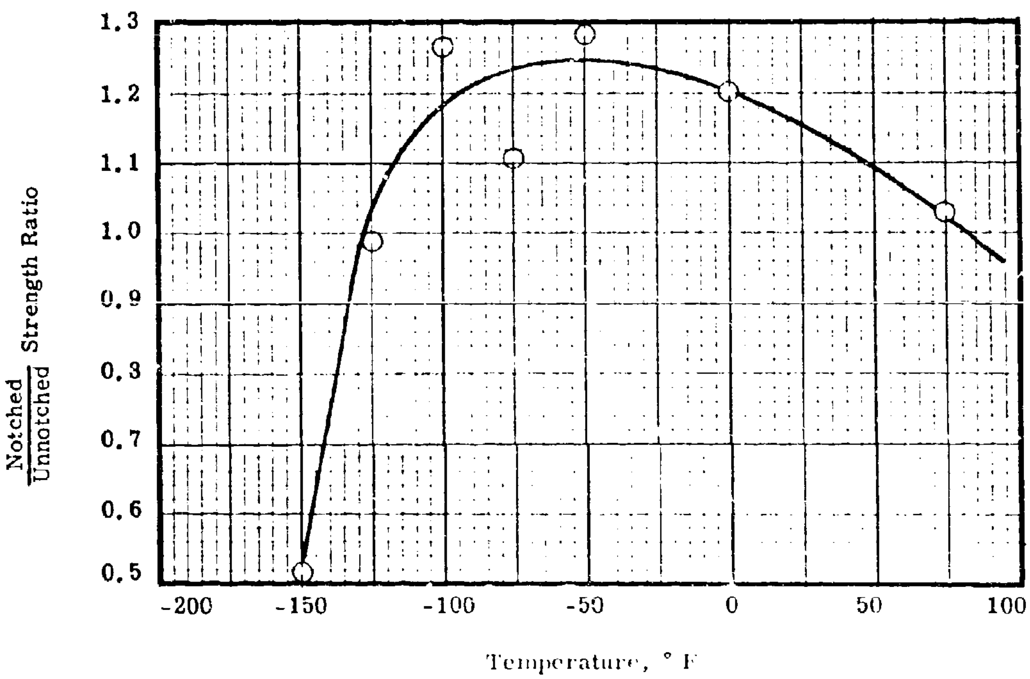


Figure 58. Notched and unnotched tensile strength and notched/unnotched tensile strength ratio at different temperatures for 0.040-in. TZM sheet in the recrystallized condition.

brittle-ductile transition zone as determined from the curves in Figures 57 and 58 is shown below:

Table XLVI

Notched-Tensile Transition Temperature of TZM Sheet

Condition	Transition Temperature Range, ° F
Optimum	-175 to -150
Recrystallized	-125 to -100

The transition temperature of the recrystallized sheet is approximately 50° F higher than that of the optimum sheet. Decreasing temperatures below 75° F had an increasing effect on the unnotched strength properties of the optimum and recrystallized sheet, with the optimum sheet having the greater strength at comparable temperatures. As expected, the ductility decreased gradually with decreasing temperature down to the ductile-brittle transition temperature (approximately -150° F for the optimum sheet and -100° F for the recrystallized sheet) beyond which the material in either condition had no measurable ductility. Generally, however, the sheet in the recrystallized condition did not have measurable ductility at temperatures below 75° F.

Notched tensile strength for the TZM sheet in both conditions increased with decreasing temperature, below 75° F, down to the brittle-ductile transition temperature, below which the strength decreased abruptly with further decreases in temperature. The temperatures at which the notched-strength ratio was unity for the optimum and recrystallized sheet are -150° F and -125° F respectively (lower parts of Figures 57 and 58).

Bend Properties

The bend-transition-temperature data for the longitudinal and transverse orientations of the 0.040-in. TZM sheet in the uncoated-optimum, uncoated-recrystallized, and the coated-optimum conditions are shown in Tables XLVII through LIV. Figures 59 through 62 show the bend angle under load at fracture (or the maximum bend angle of specimens that did not crack) as functions of temperature for longitudinal and transverse orientation of the TZM sheet in different conditions. The bend-transition temperatures, based on the lowest

Table XLVII

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction of 0.040-In. TZM Sheet
In the Optimum Condition, 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[1]	Bend Angle After Spring-back - Deg.	Springback Angle Deg.
113	55	75	103+	91	12
116	55	-50	106+	92	14
121	55	-138	107+	92	15
117	55	-150	104+	90	14
122	55	-162	106+	91	15
118	55	-175	64	-	-
119	55	-200	47	-	-
120	55	-220	10	-	-
113	56	75	105+	94	11
115	56	-50	106+	92	14
120	56	-125	107+	93	14
119	56	-138	80	-	-
121	56	-138	106+	91	15
118	56	-150	66	-	-
116	56	-158	111+	95	16
117	56	-175	104+	-	-
122	56	-200	103	-	-

[1]A plus (+) after bend angle denotes that specimen did not fracture.

Table XLVIII

Data for Determination of the Bend-Transition Temperature
in the Transverse Direction of 0.040-In. TZM Sheet
In the Optimum Condition, 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. ° F	Bend Angle Under Load at Fracture-Deg.[1]	Bend Angle After Spring-back - Deg.	Springback Angle Deg.
163	55	75	107+	93	14
166	55	-100	107+	93	14
168	55	-125	106+	90	16
172	55	-125	105+	90	15
170	55	-138	40	-	-
171	55	-138	51	-	-
169	55	-150	26	-	-
167	55	-175	29	-	-
165	56	-50	105+	92	13
166	56	-100	106+	91	15
167	56	-125	107+	92	15
168	56	-138	83	-	-
170	56	-138	106+	90	16
169	56	-150	22	-	-

[1] A plus (+) after bend angle denotes that the specimen did not fracture.

Table IL

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction of 0.040-In. TZM Sheet in the Recrystallized Condition, 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[1]	Maximum Load Lb.	Remarks
123	55	- 20	116+	95	>90° bend
126	55	- 40	90+	95	90° bend
129	55	- 50	97+	100	>90° bend
125	55	- 55	14	95	Fractured
128	55	- 60	77	100	"
124	55	- 65	18	95	"
127	55	- 70	40	100	"
131	55	- 75	74	100	"
130	55	-100	29	85	"
132	55	-125	19	80	"
131	56	- 40	92+	90	>90° bend
125	56	- 50	96+	100	" "
130	56	- 55	63	95	Fractured
123	56	- 60	69	100	"
128	56	- 65	21	95	"
126	56	- 70	16	95	"
124	56	- 75	65	105	"
132	56	- 80	41	100	"
127	56	-100	19	105	"

[1]A plus (+) after bend angle indicates specimen did not fracture.

Table L

Data for Determination of the Bend-Transition Temperature in the Transverse Direction of 0.040-In. TZM Sheet in the Recrystallized Condition, 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[1]	Maximum Load Lb.	Remarks
180	55	+65	93+	80	>90° bend
182	55	+60	31	80	Fractured
178	55	+55	93+	80	>90° bend
181	55	+50	53	90	Fractured
175	55	+45	43	85	"
173	55	+35	49	85	"
174	55	+25	12	70	"
176	55	+15	27	85	"
179	55	0	14	75	"
177	55	-50	14	95	"
180	56	+75	92+	80	>90° bend
174	56	+60	93+	55	>90° bend
175	56	+50	73	85	Fractured
182	56	+45	92	95	>90° bend
181	56	+35	46	85	Fractured
179	56	+25	79	85	"
177	56	+15	46	90	"
176	56	0	43	85	"
178	56	-15	46	100	"
173	56	-50	19	105	"

[1] A plus (+) after bend angle indicates specimen did not fracture.

Table LI

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction of 0.040-In. TZM Sheet in the Coated-Optimum Condition[1], 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[2]	Maximum Load Lb.	Remarks
142	55	75	20	65	Fractured
149	55	90	30	110	"
152	55	100	91+	100	>90° bend
147	55	100	27	90	Fractured
135	55	100	36	100	"
141	55	105	37	100	"
139	55	105	95+	95	>90° bend
143	55	110	94+	95	" "
144	55	125	95+	95	" "
133	56	75	94+	100	>90° bend
139	56	75	17	50	Fractured
144	56	90	21	50	"
152	56	95	82	100	"
134	56	100	31	45	"
146	56	100	94+	75	>90° bend
142	56	105	94+	80	" "
147	56	105	97+	95	" "
140	56	110	96+	85	" "
141	56	125	94+	95	" "

[1]Specimens were coated with the W-3 coating by Chromalloy.

[2]A plus (+) after bend angle indicates specimen did not fracture.

Table LII

Data for Determination of the Bend-Transition Temperature in the Transverse Direction of 0.040-In. TZM Sheet in the Coated-Optimum Condition[1], 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. ° F	Bend Angle Under Load at Fracture-Deg.[2]	Maximum Load Lb.	Remarks
202	55	80	20	75	Fractured
201	55	100	29	100	"
184	55	100	93 +	95	>90° bend
193	55	105	92 +	90	" "
188	55	105	91 +	95	" "
200	55	110	31	100	Fractured
194	55	110	95 +	100	>90° bend
199	55	115	78	100	Fractured
198	55	120	93 +	100	>90° bend
196	55	120	92 +	100	" "
183	56	80	22	110	Fractured
189	56	85	19	85	"
191	56	90	94 +	105	>90° bend
195	56	90	16	60	Fractured
192	56	95	63	100	"
193	56	95	94 +	100	>90° bend
188	56	100	95 +	100	" "
198	56	105	26	105	Fractured
202	56	105	93 +	105	>90° bend

[1]Specimens were coated with the W-3 coating by Chromalloy.

[2]A plus (+) after bend angle indicates specimen did not fracture.

Table LIII

Data for Determination of the Bend-Transition Temperature in the Longitudinal Direction of 0.040-In. TZM Sheet in the Coated-Optimum Condition[1], 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[2]	Maximum Load Lb.	Remarks
138	55	75	14	50	Fractured
151	55	80	42	100	"
146	55	85	38	105	"
137	55	90	45	100	"
134	55	90	96+	95	>90° bend
140	55	95	42	105	Fractured
150	55	95	33	90	"
148	55	100	93+	70	>90° bend
145	55	150	94+	100	" "
136	55	250	96+	90	" "
136	56	75	18	75	Fractured
145	56	80	92+	90	>90° bend
148	56	90	47	60	Fractured
151	56	95	75	90	"
135	56	100	35	80	"
137	56	105	47	75	"
150	56	110	94+	100	>90° bend
149	56	125	96+	95	" "
143	56	150	96+	95	" "
138	56	200	94+	70	" "

[1]Specimens were coated with the PFR-6 coating by Pfaudler.

[2]A plus (+) after bend angle indicates specimen did not fracture.

Table LIV

Data for Determination of the Bend-Transition Temperature in the Transverse Direction of 0.040-In. TZM Sheet in the Coated-Optimum Condition[1], 4t Punch Radius

Specimen No.	Sheet No.	Evaluation Temp. °F	Bend Angle Under Load at Fracture-Deg.[2]	Maximum Load Lb.	Remarks
191	55	80	29	95	Fractured
189	55	90	43	80	"
197	55	90	94+	100	>90° bend
185	55	95	34	100	Fractured
186	55	95	96+	110	>90° bend
195	55	100	93+	90	" "
190	55	105	34	105	Fractured
192	55	105	95+	100	>90° bend
183	55	110	95+	105	" "
184	56	80	33	100	Fractured
201	56	100	38	100	"
194	56	105	41	105	"
197	56	110	38	105	"
190	56	110	95+	100	>90° bend
196	56	115	41	110	Fractured
185	56	115	38	110	"
186	56	120	94+	105	>90° bend
199	56	120	95+	100	" "
200	56	125	94+	100	" "

[1]Specimens were coated with the PFR-6 coating by Pfaudler.

[2]A plus (+) after bend angle indicates specimen did not fracture.

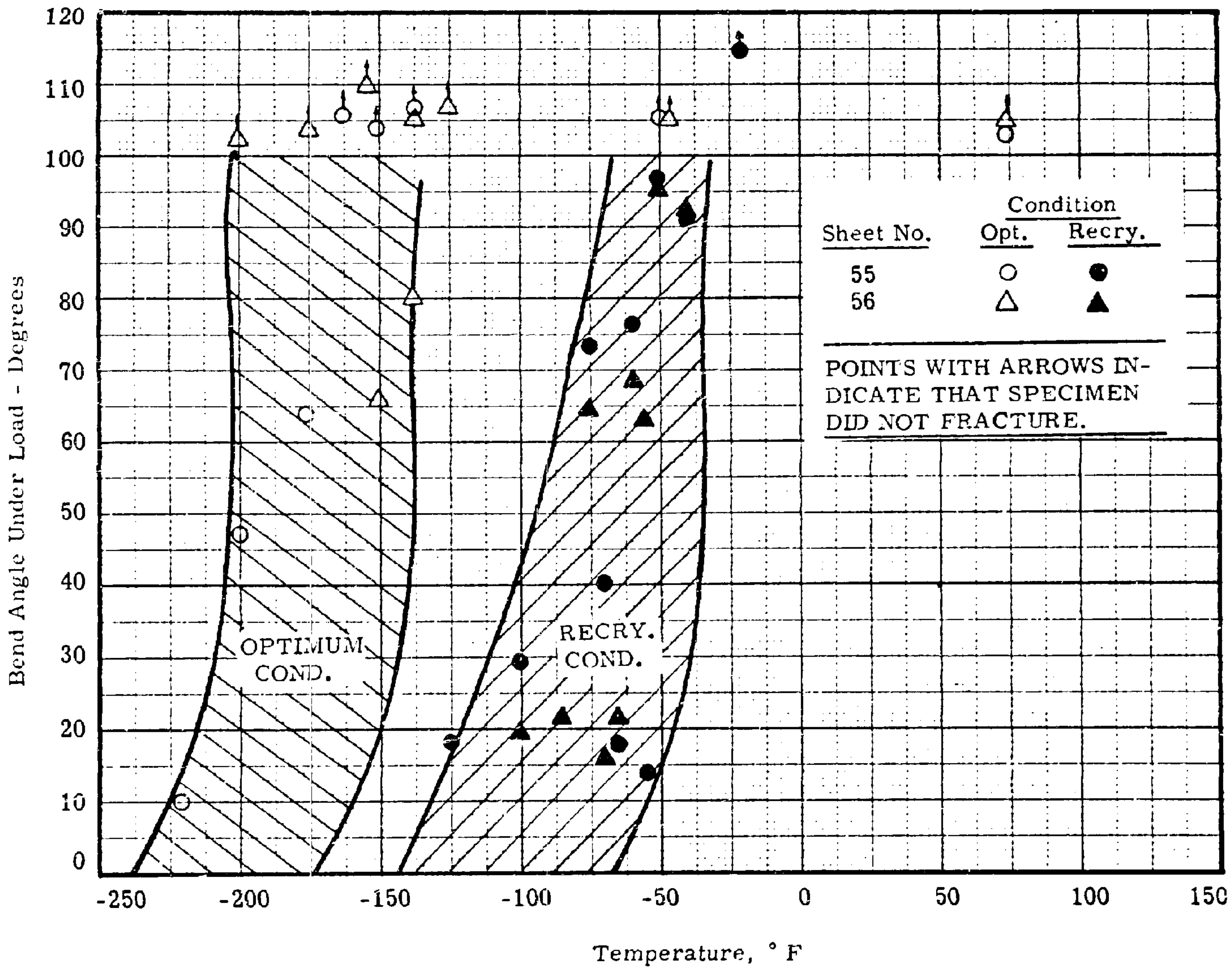


Figure 59. Bend-transition temperature curves based on bend angle under load for the longitudinal orientation of 0.040-in. TZM sheets in the optimum and recrystallized conditions. Punch radius 4t.

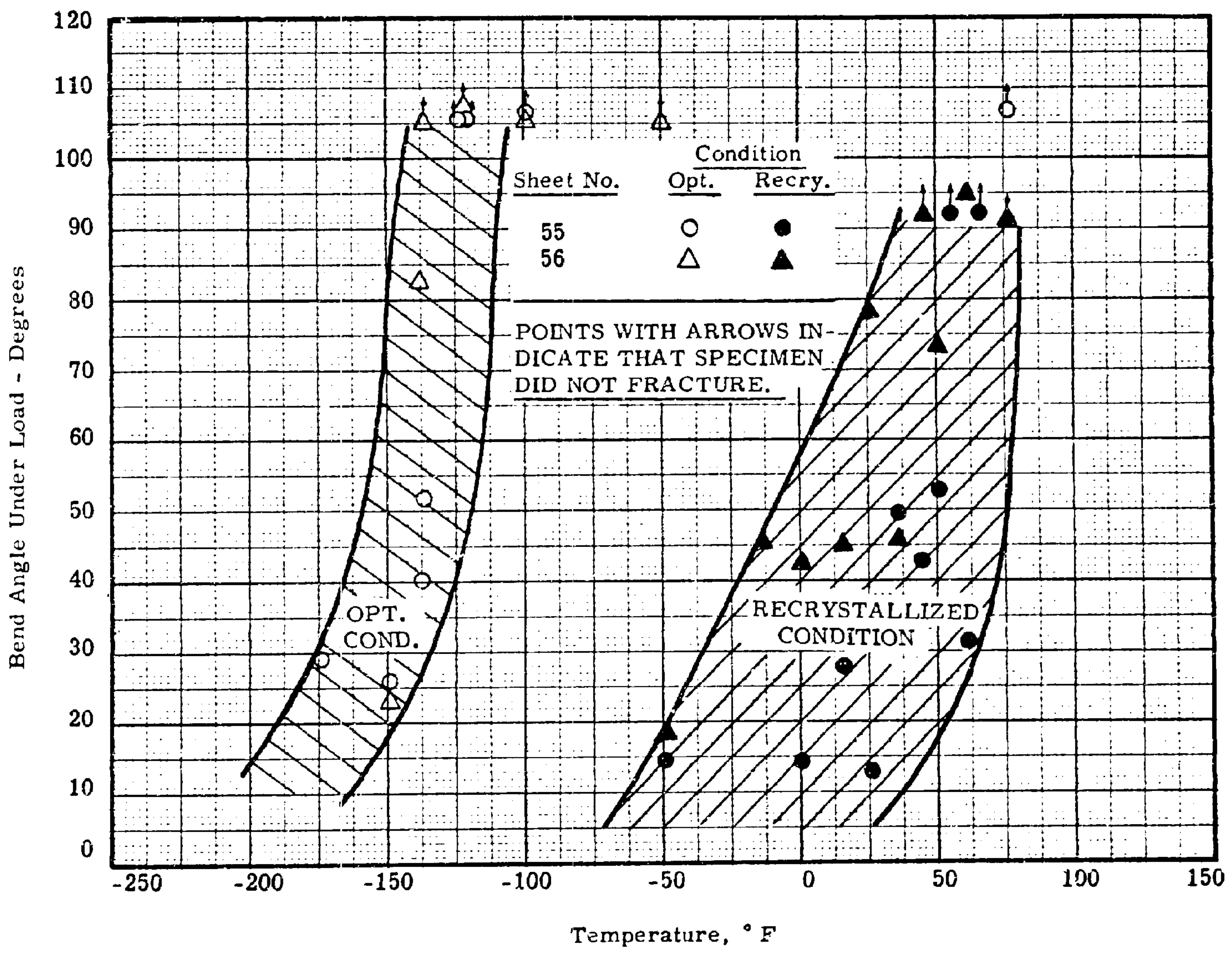


Figure 60. Bend-transition-temperature curves based on bend angle under load for the transverse orientation of 0.040-in. TZM sheets in the optimum and recrystallized conditions. Punch radius 4t.

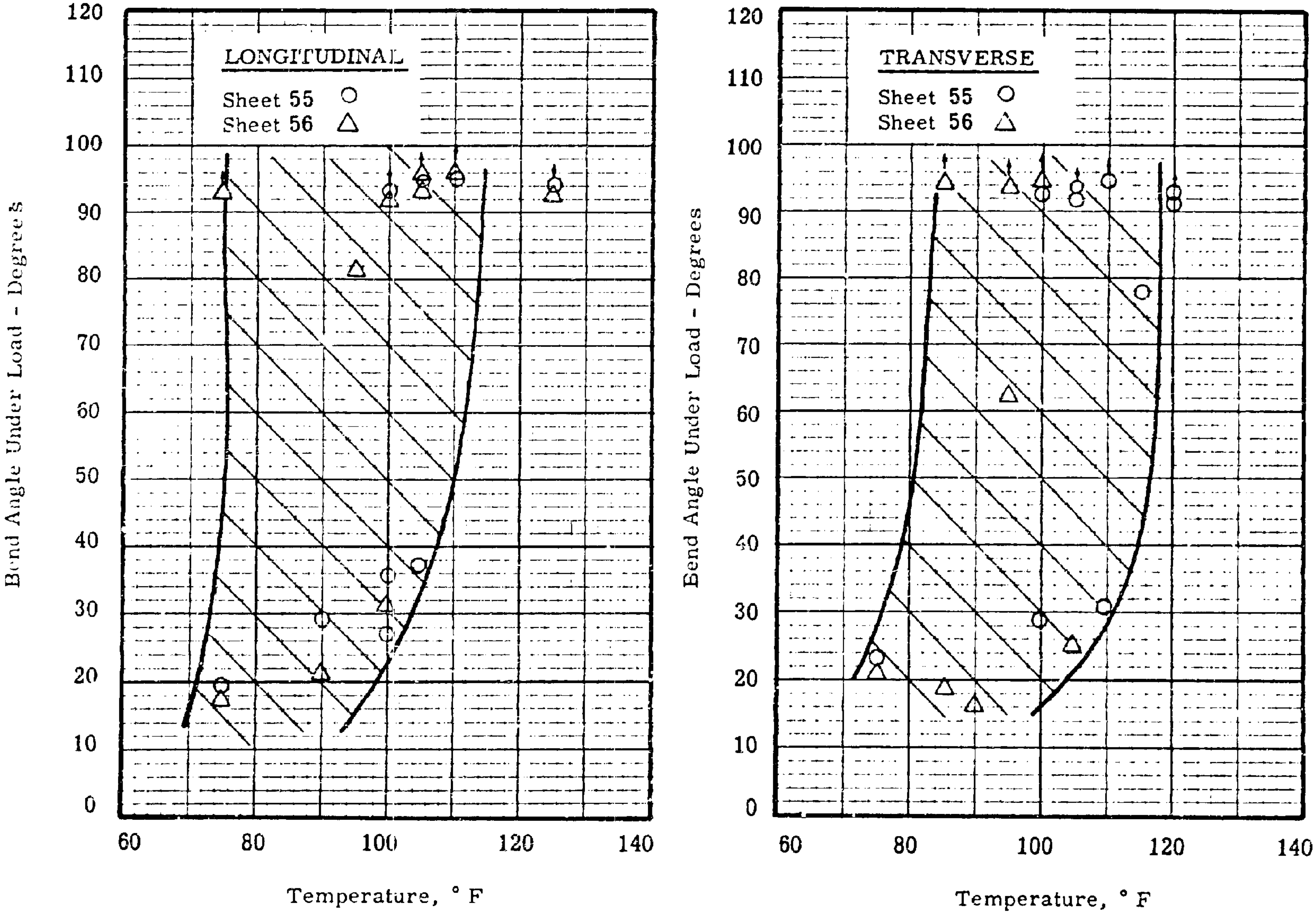


Figure 61. Bend-transition-temperature curves based on bend angle under load for the longitudinal and transverse orientation of 0.040-in. TZM sheets with W3 coating in the optimum condition. Punch radius 4t.

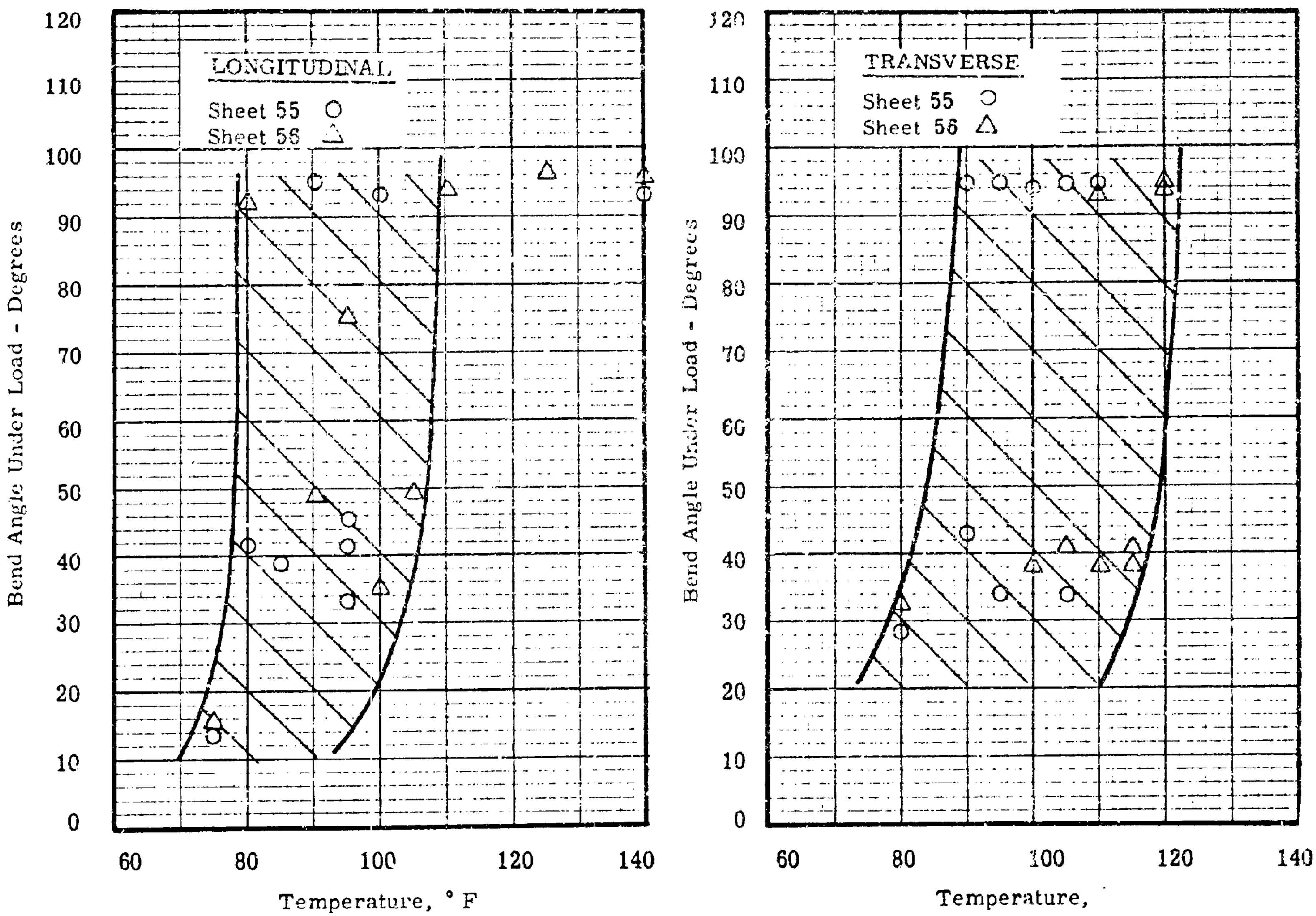


Figure 62. Bend-transition-temperature curves based on bend angle under load for the longitudinal and transverse orientation of 0.040-in. TZM sheets with PFR-6 coating in the optimum condition. Punch radius 4t.

temperature at which a 90-degree bend was accomplished and the highest temperature at which fracture occurred before a 90-degree bend was accomplished, are summarized in Table LV:

Table LV

Bend-Transition Temperatures of Uncoated and Coated TZM Sheet, 4t Punch Radius

Orientation	Condition	Surface Condition	Bend-Transition Temperature, °F
Longitudinal	Optimum	Uncoated	-200 to -137
Transverse	Optimum	Uncoated	-50
Longitudinal	Recrystallized	Uncoated	-137
Transverse	Recrystallized	Uncoated	45 to 60
Longitudinal	Optimum	W-3 Coating	75 to 105
Transverse	Optimum	W-3 Coating	85 to 115
Longitudinal	Optimum	PFR-6 Coating	80 to 105
Transverse	Optimum	PFR-6 Coating	90 to 115

It is apparent from the data shown in this table that orientation had a definite effect on the bend-transition temperature of the uncoated sheet but not for the coated sheet. The average transition temperature for the longitudinal orientation was significantly lower than for the transverse orientation for the uncoated-optimum condition and the recrystallized conditions. The recrystallization treatment increased the bend-transition temperature. The transition temperature for the recrystallized condition was approximately 120° F (longitudinal) to 185° F (transverse) greater than the respective orientations in the uncoated-optimum condition. However, the transition temperatures for both orientations, although different for the uncoated-optimum condition, are approximately equal in the coated-optimum condition. The bend-transition data show that the transition temperature was increased significantly by application of the W-3 and PFR-6 coatings to the optimum sheet. Both coatings affect the bend-transition temperature to approximately the same degree. During evaluation of the coated specimens, it was observed that the coatings on numerous specimens flaked off in the high stress areas of the bend. When this occurred, the specimens were more ductile and would usually undergo a 90° bend. However, on other specimens where flaking did not occur, the material was very brittle and only in a few cases was a 90° bend obtained.

Compressive Strength

Results of the compression tests at room temperature for the 0.040-in. TZM sheet in the optimum and recrystallized conditions are summarized in Table LVI. The compressive yield strength at 0.2% offset is about 20% lower for the longitudinal than for the transverse orientation in the optimum condition, but in the recrystallized condition it is only approximately 5% lower, which probably is not statistically significant. The large difference in the yield strengths between the two orientations in the optimum condition is probably due to the stress reversal between longitudinal rolling and compression testing in the longitudinal direction, which would cause the longitudinal yield strength to be lower than the transverse yield strength (Bauschinger effect). This same effect was also observed in the tungsten sheet, as mentioned earlier. The recrystallization heat treatment lowered the compressive yield strength significantly, and mitigated the difference in the compressive yield strength between the two sheet orientations. In comparison, the yield strength in compression (Table LVI) was generally lower than the yield in tension (Tables XXXVII and XXXVIII).

The modulus of elasticity in compression varied somewhat between orientations for the two heat-treated conditions, however this variation is probably not statistically significant. The elastic modulus in compression is lower than in tension by approximately 7 million psi, which is probably a significant difference.

Shear and Bearing

Results of the room temperature shear evaluations are summarized in Table LVII. The shear strength of the TZM sheet is approximately 35% less than the tensile strength at room temperature (Table XXXVII), which is normal for most metals. Table LVIII shows the bearing strength data. The average bearing strength at 2% deformation of the bearing hole was about 185 ksi, while the ultimate bearing strength was 260 ksi.

Creep

The summary in Table LIX shows the time to 1% creep deformation at different temperatures and stresses for the optimum TZM sheet. Time-deformation curves for each evaluation are shown in Figures 63 and 65 for the 2000° F and 2500° F tests respectively. Time to 1% deformation was read from these curves and plotted against stress in Figures 64 and 66. The time-stress curves indicate that the TZM sheet will creep 1% in 100 hours under

Table LVI

Compression Properties of 0.040-In. TZM Sheet at Room Temperature in the Optimum[1] and Recrystallized Conditions[2]

Optimum Condition				Recrystallized Condition			
Specimen No.	Direction	0.2%-Offset Yld. Str. ksi	Mod. of Elasticity 10^6 psi	Specimen No.	Direction	0.2%-Offset Yld. Str. ksi	Mod. of Elasticity 10^6 psi
55-97	Long.	103.6	40.1	55-98	Long.	73.0	45.0
55-99	Long.	100.9	36.8	55-100	Long.	70.3	42.7
56-97	Long.	101.9	43.1	56-98	Long.	67.3	42.9
56-99	Long.	101.7	43.1	56-100	Long.	69.5	45.1
Average	Long.	102.0	40.8	Average	Long.	70.0	43.9
55-101	Trans.	127.7	37.3	55-102	Trans.	74.5	32.0
55-103	Trans.	125.0	43.6	55-104	Trans.	73.9	44.2
56-101	Trans.	126.0	38.1	56-102	Trans.	69.8	42.6
56-103	Trans.	123.8	39.5	56-104	Trans.	70.3	45.0
Average	Trans.	125.6	39.6	Average	Trans.	72.1	41.0

[1]Sheet was hot-warmed rolled and annealed for one hour at 2300°F.

[2]Specimens were recrystallized at 2475°F in one hour in a vacuum of 10^{-4} torr.

Table LVII

Shear Strength at Room Temperature of 0.040-In. TZM Sheet[1]

	Shear Strength[2] ksi
	84.3
	83.0
	88.0
Average	85.1

[1]Optimum Condition; major axis in longitudinal direction

[2]Based on area = shear path distance x sheet thickness

Table LVIII

Bearing Strength at Room Temperature of 0.040-In. TZM Sheet[1] (e/D = 1.5)

	Bearing Strength[2] at 2% Offset ksi	Ultimate Bearing Strength[2] ksi	Approximate Percent of Deformation at Fracture
	183.0	260.0	19.2
	183.0	258.0	19.3
	185.0	257.0	18.5
	190.0	264.0	18.5
Average	185.3	259.8	18.9

[1]Optimum Condition; major axis in longitudinal direction

[2]Based on area = sheet thickness x bearing hole diameter

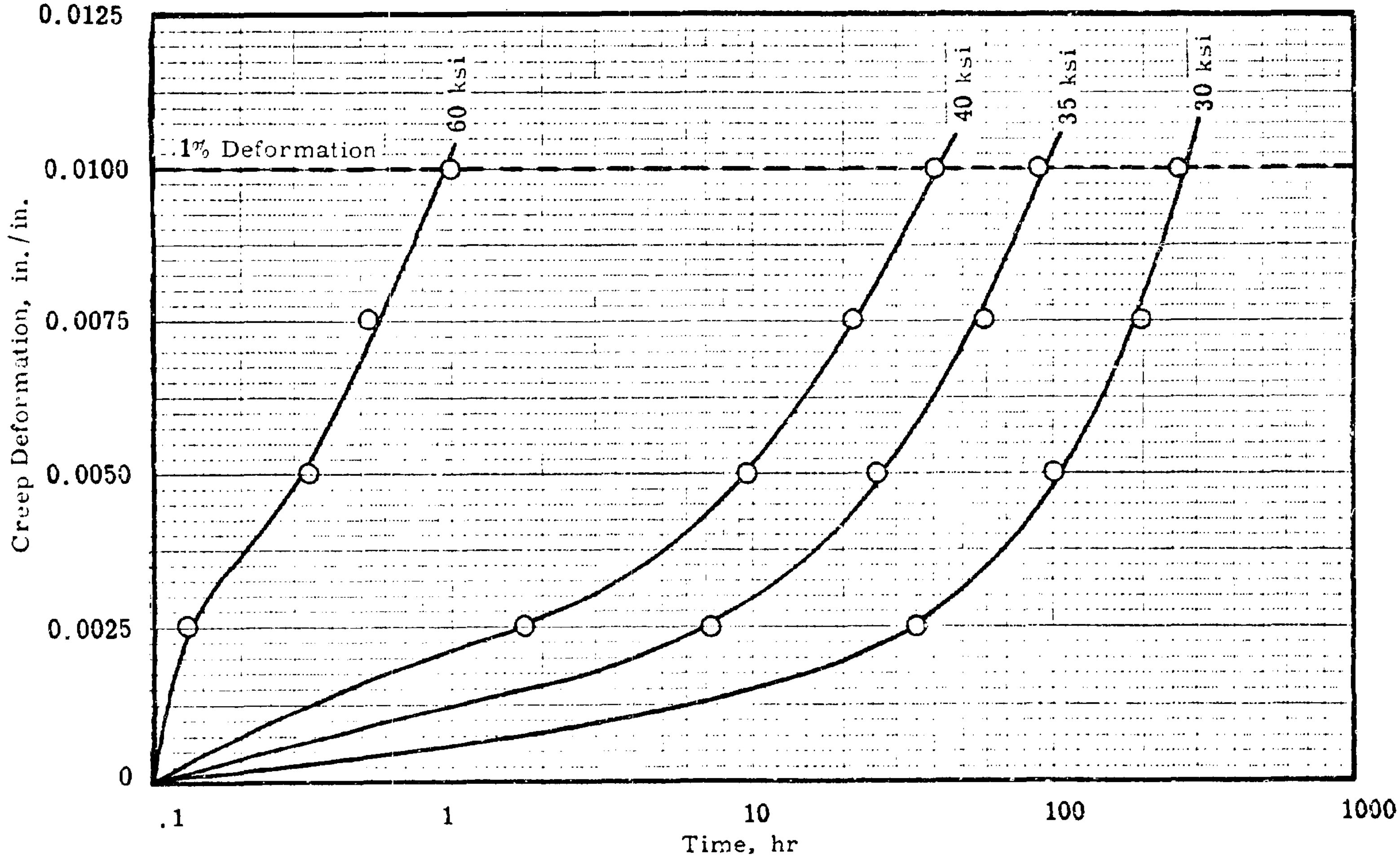


Figure 63. Time-deformation curves for 0.040-in. TZM sheet at 2000°F and different stresses

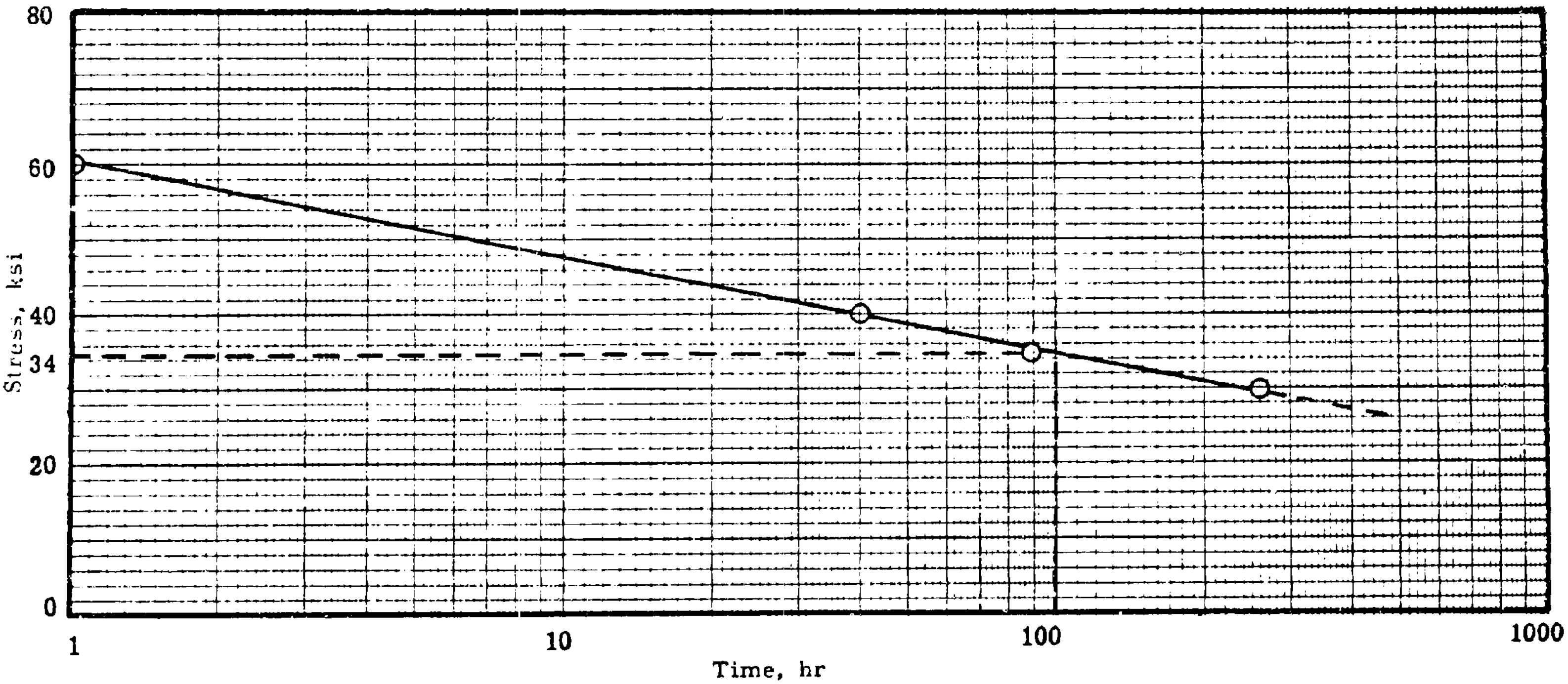


Figure 64. Effect of stress on time to 1% creep deformation at 2000°F for 0.040-in. TZM sheet

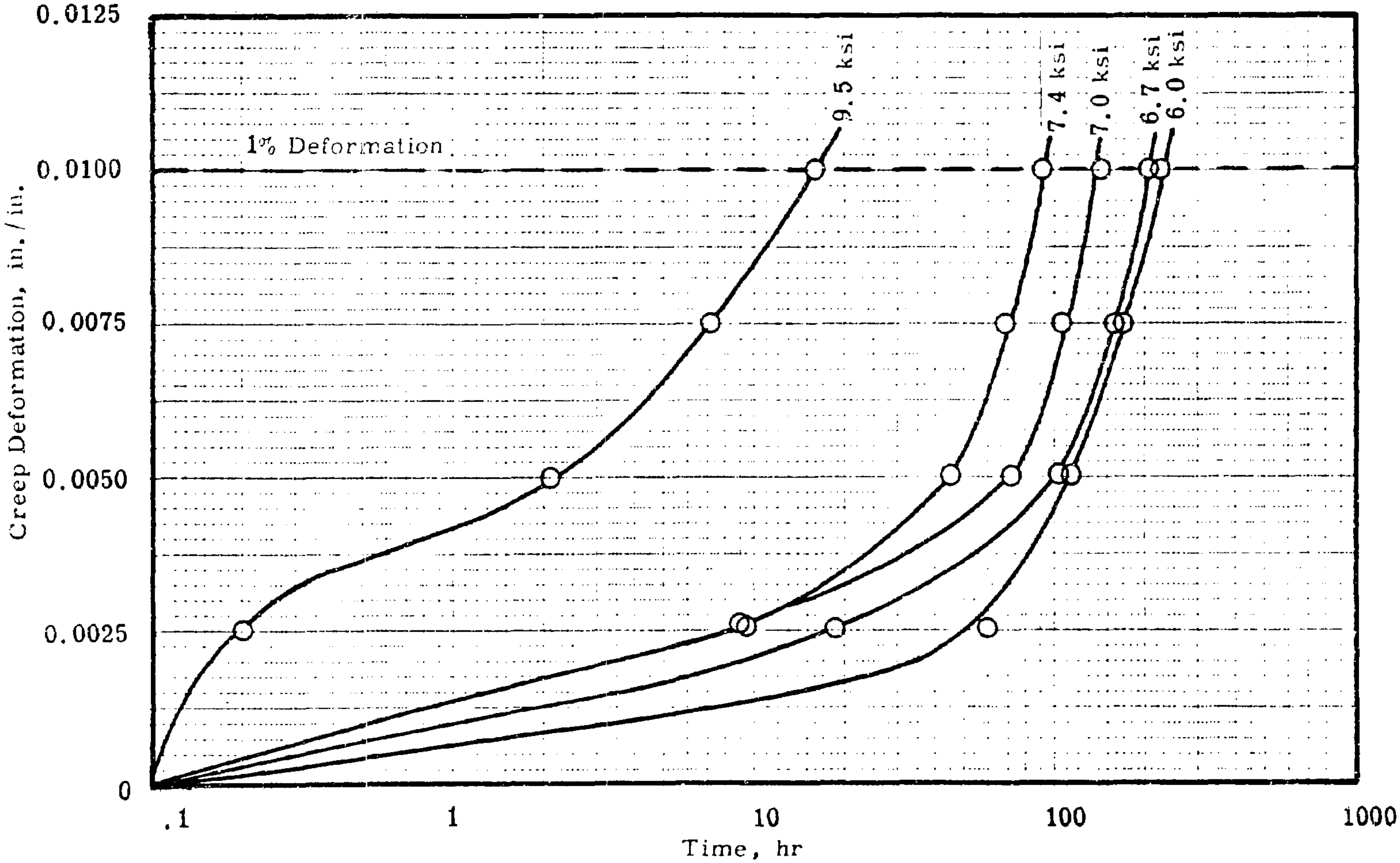


Figure 65. Time-deformation curves of 0.040-in. TZM sheet at 2500°F and different stresses

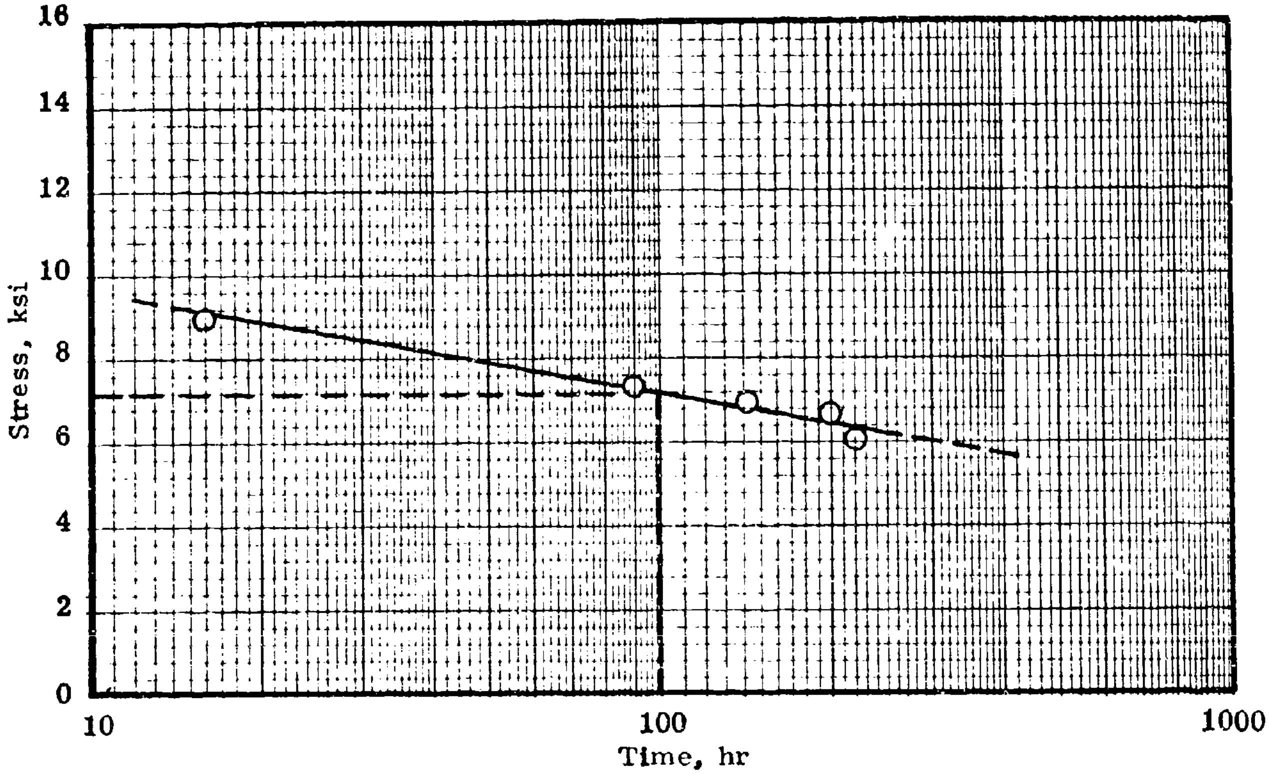


Figure 66. Effect of stress on time to 1% creep deformation at 2500° F for 0.040-in. TZM sheet.

stresses of approximate 34 ksi and 7.2 ksi at 2000° F and 2500° F respectively. As expected, a much lower stress was required to produce the specified creep rate at 2500° F than at 2000° F because the optimum structure was recrystallized during evaluation at the higher temperature.

Table LIX

Summary of Time to 1% Creep Deformation for 0.040-In. TZM Sheet in the Optimum Condition

Temperature ° F	Stress, ksi	Time, hr
2000	60	1
2000	40	40
2000	35	89
2000	30	260
2500	9.5	16
2500	7.4	90
2500	7.0	143
2500	6.7	201
2500	6.0	223

Thermal Stability

The creep exposed specimens discussed in the preceeding section were further evaluated at room temperature to determine the residual tensile properties. The results of these evaluations are summarized in Table LX. The residual tensile properties show that creep exposure to 2000° F had no significant effect on the normal tensile properties (Table XXXVII) of the optimum TZM sheet. However, creep exposure at 2500° F, in addition to recrystallizing the structure, apparently affected the normal recrystallized tensile properties (Table XXXVIII) to a varying degree, dependent upon the creep conditions of stress and exposure time to 0.1% deformation as indicated by the residual properties. No correlation of residual properties with the exposure parameters was apparent from the limited evaluations. The minimum residual strength and ductility, which were significantly lower than the normal recrystallized tensile properties, were obtained from a specimen elongated 0.1% by creep in 143 hours at 2500° F and a stress of 7 ksi. The residual tensile properties of some creep-exposed specimens were higher than the normal properties of the sheet in the recrystallized condition.

Table LX

Tensile Properties at Room Temperature of TZM Sheet After Creep-Exposure to 1% Deformation at 2000°F or 2500°F

Creep Data			0.2%-Offset	Ultimate	Elongation	Modulus of	Radiation
Temperature °F	Stress ksi	Time hours to 1.0%	Yld. Str. ksi	Ten. Str. ksi	in. 1 in. %	Elasticity x 10^6 psi	of Area %
2000	60	1	118.0	128.0	16	44	30
2000	40	40	120.0	120.0	20	45	41
2000	35	89	116.0	126.0	17	47	40
2000	30	260	-[2]	> 97.0	-[2]	48	-[2]
2500	9.5	16	80.0	83.0	38	51	56
2500	7.4	90	59.8	72.9	5	48	-[3]
2500	7.0	143	64.6	66.7	1	53	-[3]
2500	6.7	201	73.3	77.3	1	43	-[3]
2500	6.0	223	80.5	84.5	35	50	40

[1]Optimum condition and longitudinal direction.

[2]Fractured before 0.2%-offset yield.

[3]No measureable reduction of area.

Fusion Weld Joint Efficiency

The results of room-temperature tensile evaluations of TZM in the as-welded and welded-heated treated conditions are shown in Table LXI for both TIG and electron-beam-welded specimens. The data indicate that the EB welds tend to have a slightly higher strength than the TIG welds under comparable conditions. A heat treatment of 2000° F for one hour in a vacuum of 10^{-5} torr apparently decreased the strength of both welds. The tensile strength of the welded material was from 30% to 40% lower than the normal longitudinal tensile strength (Table XXXVII) of the TZM sheet in the optimum condition, varying with the method of welding and the weld condition. The EB and TIG welded material had no appreciable ductility as opposed to 21% elongation and 42% reduction-of-area for the unwelded TZM sheet in the optimum condition.

Density

The results of density measurements from samples of the different sheets and gages of the TZM sheet material are shown in Table LXII. The slight differences in density of the three different sheet thicknesses is probably not significant.

Table LXII

Density of TZM Sheet

Sheet No.	Sheet gage, In.	Density[1] g/cc
74	0.020	10.13
55	0.040	10.16
56	0.040	10.16
23	0.060	10.15

[1] Measurements were made at temperature of 26.3° C (79.3° F).

Thermal Expansion

The thermal expansion of the TZM sheet was determined to 2500° F. The data are given in Tables vii-b and viii-b of Appendix B and in Figure 67.

Table LXI

Room-Temperature Tensile Properties of Fusion-Welded 0.040-In. TZM Sheet in the As-Welded and Heat-Treated Conditions

Specimen Number	Welding Method	0.2%-Offset Yld. Str. ksi	Ultimate Ten. Str. ksi	Modulus at Elasticity x 10^6 psi	Elongation in. 1 in. %	Condition
55-3	EB	97.5	104.0	36	1	As - Welded
56-3	EB	-[1]	84.0	45	-	As - Welded
55-7	TIG	75.6	88.3	39	2	As - Welded
56-7	TIG	75.6	79.6	39	1	As - Welded
55-1	EB	90.0	90.0	37	-	Welded and Heat Treated[2]
56-1	EB	-[1]	90.0	46	-	Welded and Heat Treated
55-8	TIG	-[1]	72.2	45	-	Welded and Heat Treated
56-8	TIG	-[1]	73.0	47	-	Welded and Heat Treated

[1]Fractured before 0.2%- offset yield.

[2]Specimens were heated to 2000°F in a vacuum of 10^{-5} torr and held one hour.

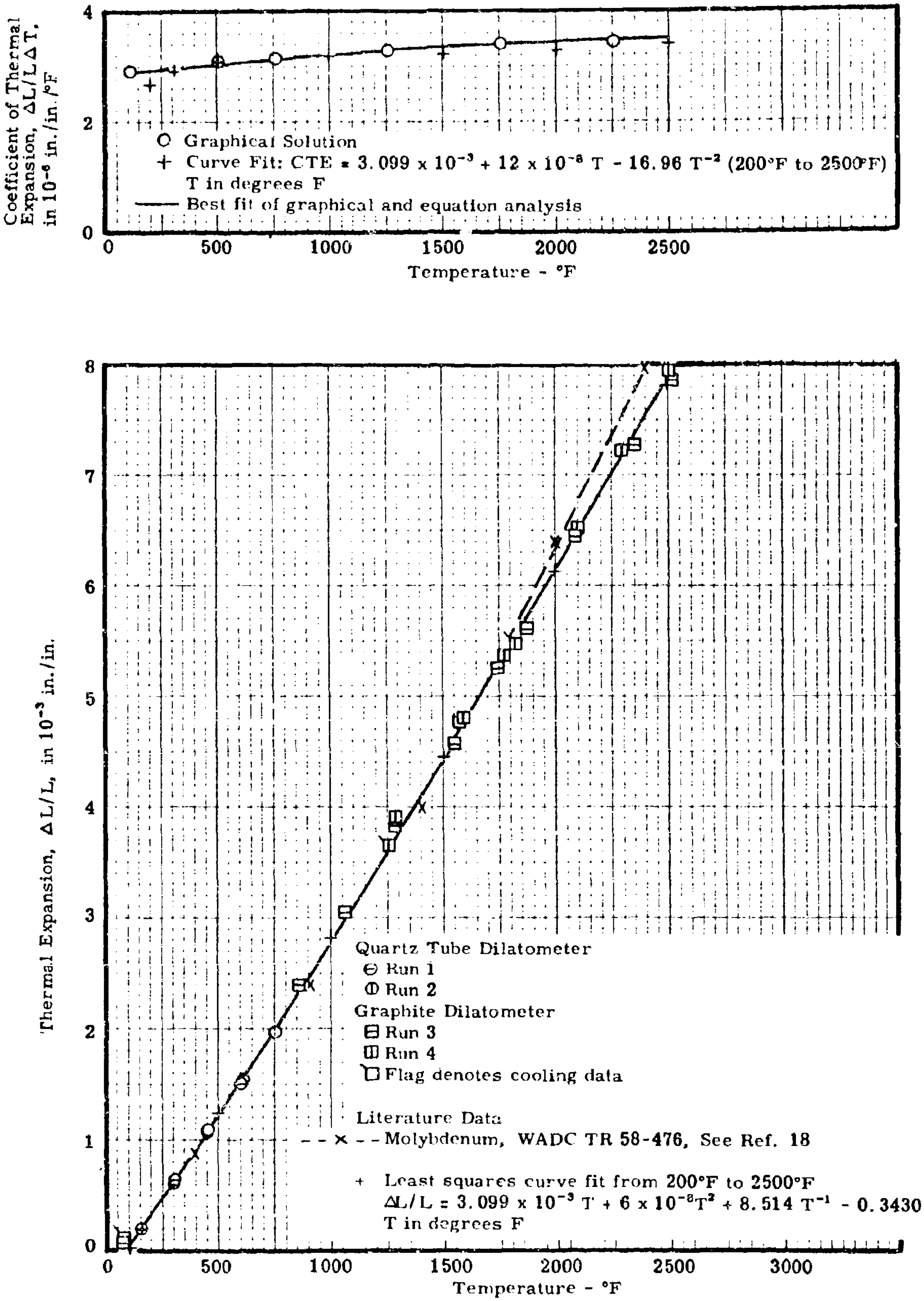


Figure 67. The thermal expansion of TZM sheet parallel to the plane of the sheet.

The total thermal expansion from room temperature to 2500° F was about 7.9×10^{-3} in./in. It was noted that the expansion at 2500° F was about 6% less than that indicated by some literature data for molybdenum, but the expansion curves up to about 1500° F were in good agreement with those reported for unalloyed molybdenum. The least squares curve fit of the expansion data is given in the following equation:

$$\Delta L/L = 3.099 \times 10^{-3} T + 6 \times 10^{-8} T^2 + 8.514\ T^{-1} - 0.3430 \qquad (g)$$

when temperature T is in degrees Fahrenheit. This equation is valid over the temperature range from about 200° F to 2500° F.

The coefficient of thermal expansion was determined graphically and by adjusting the derivative of Equation (g) as discussed earlier. The resulting equation for the coefficient of thermal expansion was:

$$CTE = 3.099 \times 10^{-3} + 12 \times 10^{-8} T - 16.96\ T^{-2} \qquad (h)$$

Points calculated with Equations (g) and (h) are plotted with the experimental data in Figure 67. As for the tungsten, the curve for the coefficient of thermal expansion represents the best fit of the graphical and mathematical solutions. This coefficient increased from about 2.9×10^{-6} in./in./° F at 100° F to about 3.5×10^{-6} in./in./° F at 2500° F.

Thermal Conductivity

The thermal conductivity data for TZM sheet are presented in Figure 68 and in Tables ix-b and x-b. The conductivity was about 825 Btu/hr/ft^2/° F/in. at 100° F and decreased to about 700 Btu/hr/ft^2/° F/in. at 1000° F. From 1000° F to 2500° F the conductivity was almost constant at about 700 Btu/hr/ft^2/° F/in. The conductivity of the TZM sheet was in good agreement with some literature data for Mo-0.5Ti, and compared to some literature values for molybdenum, was about 13 percent lower at 100° F, about the same at 2000° F, and about 10 percent higher at 2500° F (18, 19).

Heat Capacity

The enthalpy and heat capacity data for the TZM sheet are shown in Figure 69 and Table xi-b. The heat capacity increased from 0.065 Btu/lb/° F at 100° F to about 0.082 Btu/lb/° F at 2500° F.

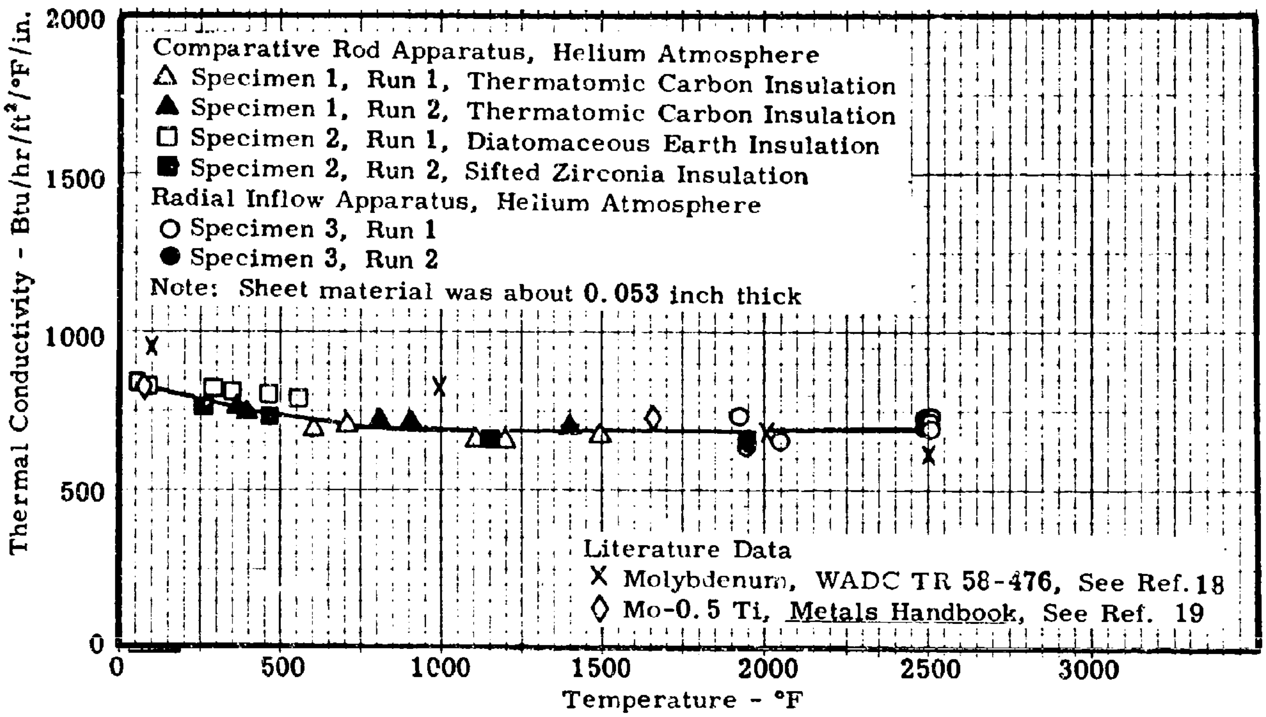


Figure 68. The thermal conductivity of TZM sheet parallel to the plane of the sheet

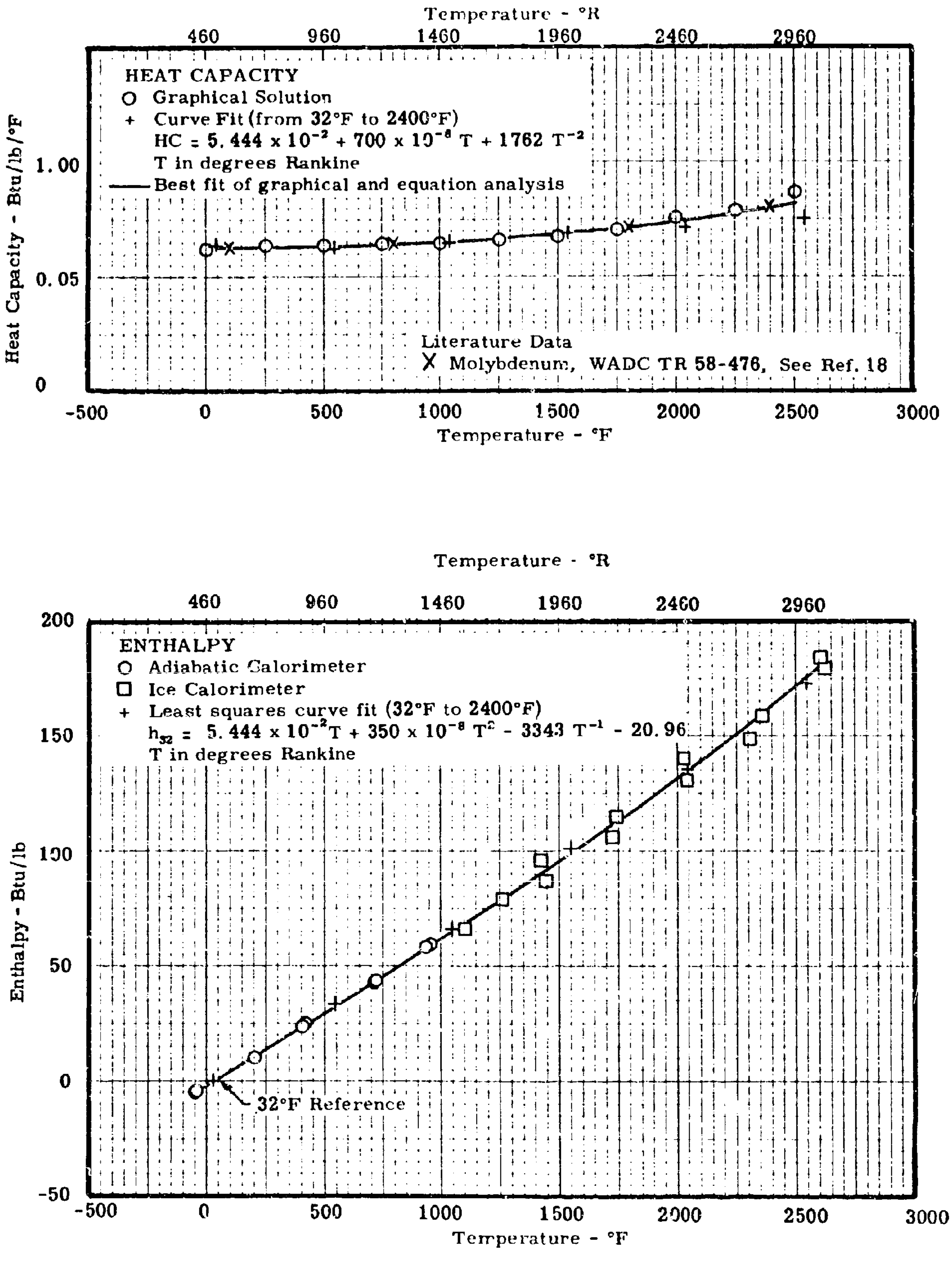


Figure 69. The enthalpy and heat capacity of TZM sheet

A least squares treatment of the enthalpy data resulted in the following equation for the enthalpy of TZM sheet from 32° F to 2400° F:

$$h_{32} = 5.444 \times 10^{-2}\ T + 350 \times 10^{-8}\ T^2 - 3343\ T^{-1} - 20.96 \qquad \text{(i)}$$

Enthalpies calculated with this equation are shown in Figure 69 with the enthalpy data and are listed in Table vi-b.

The derivative of the enthalpy equation was adjusted to agree with the graphically determined heat capacity at 500° F (40° F) to obtain the following equation for heat capacity:

$$HC = 5.444 \times 10^{-2} + 700 \times 10^{-8}\ T + 1762\ T^{-2} \qquad \text{(j)}$$

This equation is valid from about 32° F to 2400° F. Values calculated from this equation are plotted in Figure 69 and listed in Table vi-b. The curve for heat capacity in Figure 69 represents the best fit of the values determined from the equation and from the graphical solution. The heat capacity of the TZM sheet was in good agreement with the data for molybdenum from several literature sources (18, 19).

Submitted by:

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Metals Evaluation Section

Approved:

J. R. Kattus

J. R. Kattus, Director
Metallurgy Research

August 31, 1966
7563-1479-XII
(65:45)cbf-fd

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APPENDIX A

Composition and Release Properties of TZM Sheet

Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 13 Sheet 74 Guage 020

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.032	.42	.088	<.0035	.0018	<.001	.0042	.0003	.0001

Recrystallization:	End A	End B
As received D.P.H.	351	327
Fully Annealed D.P.H.	222	214
Rex. Temp. (°F)	2500	2450
% Recrystallized:	60	50
% Hardness Drop	78	67

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S.(KSI)	% Elong.
End A Transverse	142.1	135.6	7.9
End A Longitudinal	131.6	120.0	9.6
End B Transverse	140.3	131.8	6.6
End B Longitudinal	134.0	120.0	12.4

Notched Tensile:	End A	End B
Longit. Notch Strength:	141.9 KSI	139.9 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S. (KSI)	% Elong.
End A Transverse	81.4	80.3	3.8
End B Transverse	79.3	75.7	3.1

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-125°F	-125°F	-150°F
Next Failed Temp.	-150°F	-150°F	-175°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	16°	20°	17°

Specimen size 1/2 x 2-1/2 Fixture Span length 1"

Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 13 **Sheet:** 74 **Guage:** 020

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .300 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .104 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .025/.027 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .020±.002 thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 10 Sheet 55 Guage 040

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.030	.49	.104	<.001	<.0015	.002	.0012	.0003	.00017

Recrystallization:	End A	End B
As received D.P.H.	304	301
Fully Annealed D.P.H.	192	195
Rex. Temp. (°F)	2450	2500
% Recrystallized:	60	70
% Hardness Drop	74	83

Room Temp. Tensile	U.T.S.(KSI)	.2% Y.S. (KSI)	% Elong.
End A Transverse	130.1	124.8	8.9
End A Longitudinal	125.0	108.4	16.2
End B Transverse	131.2	124.6	12.0
End B Longitudinal	130.7	113.3	15.5

Notched Tensile:	End A	End B
Longit. Notch Strength:	133.1 KSI	135.1 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S.(KSI)	% Elong.
End A Transverse	80.4	75.2	5.0
End B Transverse	81.5	78.3	4.7

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-50°F	-100°F	-150°F
Next Failed Temp.	-75°F	-125°F	-175°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	6°	6°	7°

Specimen size 1/2 x 2-1/2 Fixture Span length 1.25"

Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 10 **Sheet:** 55 **Guage:** 040

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .540 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .187 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .044/.048 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .040±.003 thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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[signature]
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Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 10 Sheet 56 Guage 040

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.031	.50	.119	<.0035	<.0015	<.001	.0015	.0002	.00024

Recrystallization:	End A	End B
As received D.P.H.	302	300
Fully Annealed D.P.H.	197	194
Rex. Temp. (°F)	2450	2450
% Recrystallized:	60	85
% Hardness Drop	68	89

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S. (KSI)	% Elong.
End A Transverse	138.6	131.7	7.3
End A Longitudinal	128.8	109.2	16.2
End B Transverse	132.4	124.2	11.5
End B Longitudinal	127.1	106.8	15.6

Notched Tensile:	End A	End B
Longit. Notch Strength:	139.4 KSI	132.0 KSI

2000°F Tensile:	U.T.S. (KSI)	Y.S (KSI)	% Elong.
End A Transverse	84.9	79.8	6.2
End B Transverse	78.5	74.9	5.4

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-100°F	-150°F	-150°F
Next Failed Temp.	-125°F	-175°F	-175°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	6°	9°	9°
Specimen size	1/2 x 2-1/2	Fixture Span length	1.25"

Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 10 **Sheet:** 56 **Guage:** 040

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .540 thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .187 thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .044/.048 thick
Anneal 1 hr @ 2300°F belt grind and pickle to .040 ±.003"thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Refractory Metal Sheet Evaluation

Material: TZM **Producer:** Universal-Cyclops Steel Corporation

Heat: KDTZM1196 **Lot:** 5 **Sheet:** 23 **Guage:** .060

Manufacturing Data:

Melt 8" dia ingot, extrude to 4-1/4" dia @ 2100°F
Anneal 1 hr @ 2800°F, InFab forge @ 3400°F to 1.5" thick
Anneal 1 hr @ 2800°F roll @ 2200°F to .760" thick
Anneal 1 hr @ 2700°F roll @ 2200°F to .264" thick
Anneal 1 hr @ 2150°F cross roll @ 1800°F to .063/.069" thick
Anneal 1 hr @ 2300°F belt grind and pickle to .060±.003" thick

Specimen Preparation:

Room temp. tensile: Mill .250" x 1.0" gage length with 1" radius
2000°F tensile: Grind .250" x 1.0" gage length with 1/4" radius
Notched R.T. Tensile: Grind .50" x 1.0" gage length with 1/4" radius and grind notch
Bend: Grind 1/16" min., from edges of blank strip. Abrasive cut length mults. De-burr edges and corners with 120 grit abrasive.

Testing Machine:

R.T. Tensile and all bends: Baldwin-Lima-Hamilton universal testing machine
2000°F tensile:

Strain Rate:

R.T. Tensile: .005"/"/' to .6% Y.S., .05"/"/' to failure (Extensometer)
Notched tensile: .005"/minute head speed.
2000°F tensile: .05"/"/' (Deflectometer)
Bends: 1"/minute ram travel

Test Environment:

2000°F Tensile: Vacuum (.5micron) induction heat to 2000°F in 15 min and hold 15 min.
Bends: Liquid nitrogen cold chamber, hold at temp. 5 minutes

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Refractory Metal Sheet Evaluation

Heat KDTZM1196 Lot 5 Sheet 23 Guage .060

Chemistry:	C	Ti	Zr	Si	Fe	Ni	O_2	N_2	H_2
%	.024	.50	.083	<.0035	<.0015	<.001	.0022	.0010	.0002

Recrystallization:	End A	End B
As received D.P.H.	304	318
Fully Annealed D.P.H.	198	208
Rex. Temp. (°F)	2450	2500
% Recrystallized:	60	50
% Hardness Drop	83	81

Room Temp. Tensile	U.T.S. (KSI)	.2% Y.S.(KSI)	% Elong.
End A Transverse	138.0	131.1	11.8
End A Longitudinal	128.6	113.1	15.1
End B Transverse	138.0	129.7	13.7
End B Longitudinal	132.4	106.1	17.4

Notched Tensile:	End A	End B
Longit. Notch Strength:	138.3 KSI	135.0 KSI

2000°F Tensile:	U.T.S.(KSI)	Y.S.(KSI)	% Elong.
End A Transverse	82.0	79.5	6.4
End B Transverse	87.2	84.7	5.9

Bend Tests	End A (Transv)	End B (Transv.	End B (Longit)
4T Minimum Bend Temp	-5[illegible]	-50°F	-50°F
Next Failed Temp.	-75 [illegible]	-75°F	-75°F
Min. bend radius @ R.T.	OT	OT	OT
Springback angle	<5°	<5°	<5°
Specimen size	3/4 x 3-1/4	Fixture Span Length 1-1/2"	

APPENDIX B

Tabulated Data for Thermal Property Evaluations

Table i-b

The Thermal Expansion of Tungsten Sheet
Using the Quartz Tube Dilatometer

Temperature °F	Time	Observed Total Elongation 10^{-3} in.	Observed Unit Elongation 10^{-3} in. /in.	Unit Elongation Correction for Dilatometer Motion 10^{-3} in. /in.	Corrected Specimen Unit Elongation 10^{-3} in. /in.
Run 1 on Specimen 1					
80.3	10:20	0	0	0	0
152	11:01	0.32	0.11	0.02	0.13
305	11:26	1.20	0.40	0.07	0.47
453	11:46	2.15	0.72	0.12	0.84
606	12:17	2.92	0.97	0.17	1.14
Run 2 on Specimen 1					
82.5	1:40	0	0	0	0
152	2:06	0.40	0.13	0.02	0.15
310	2:30	1.37	0.46	0.07	0.53
450	2:57	2.28	0.76	0.12	0.88
600	3:50	3.32	1.11	0.16	1.27
748	4:15	4.25	1.42	0.21	1.63

Initial length: 3.001 inch
Final length: 3.001 inch
(Both Runs)

Table ii-b

The Thermal Expansion of Tungsten Sheet
Using the Graphite Dilatometer

Temperature °F	Time	Observed Total Elongation 10^{-3} in.	Observed Unit Elongation 10^{-3} in. /in.	Unit Elongation Correction for Dilatometer Motion 10^{-3} in. /in.	Corrected Specimen Unit Elongation 10^{-3} in. /in.
Run 3 on Specimen 1 (Dilatometer No. 4)					
70	9:00	0	0	0	0
880	9:50	3.98	1.33	0.81	2.14
1101	10:30	4.85	1.62	1.06	2.68
1295	11:05	5.58	1.86	1.28	3.14
1519	11:55	6.33	2.11	1.53	3.64
1535	11:56	6.07	2.02	1.54	3.56
1770	12:50	6.70	2.23	1.83	4.06
2120	1:30	8.01	2.67	2.31	4.98
2290	2:00	8.60	2.86	2.50	5.36
2500	3:05	9.44	3.15	2.80	5.95
1875	3:25	6.96	2.32	1.98	4.30
1366	3:50	5.18	1.73	1.36	3.09
751	4:25	2.67	0.89	0.69	1.58
70	8:00	0.05	0.02	0	0.02
Initial length:	3.001 inches				
Final length:	3.002 inches				
Run 4 on Specimen 1 (Dilatometer No. 4)					
70	8:50	0	0	0	0
912	9:25	3.61	1.20	0.85	2.05
1103	9:55	4.39	1.46	1.07	2.53
1290	10:30	5.11	1.70	1.27	2.97
1518	11:29	5.97	1.99	1.53	3.52
1535	11:30	5.99	2.00	1.55	3.55
1820	12:20	7.02	2.34	1.91	4.25
2095	1:00	8.05	2.68	2.25	4.93
2295	1:35	8.70	2.90	2.50	5.40
2475	2:30	9.31	3.10	2.76	5.86
2500	2:55	9.38	3.12	2.80	5.92
1520	3:20	5.48	1.83	1.53	3.36
70	8:00	-0.05	-0.02	0	-0.02
Initial length:	3.002 inches				
Final length:	3.002 inches				

Table ii-b (Cont'd)

Temperature °F	Time	Observed Total Elongation 10^{-3} in.	Observed Unit Elongation 10^{-3} in./in.	Unit Elongation Correction for Dilatometer Motion 10^{-3} in./in.	Corrected Specimen Unit Elongation 10^{-3} in./in.
Run 5 on Specimen 1 (Dilatometer No. 1)					
70*	10:00	0	0	0	0
897*	10:40	3.33	1.11	0.75	1.86
1092*	11:25	4.02	1.34	0.95	2.29
1312*	12:10	4.81	1.60	1.25	2.85
1514*	1:20	5.51	1.84	1.50	3.34
1540	1:21	5.52	1.84	1.55	3.39
1700	1:49	6.14	2.05	1.78	3.83
1685*	1:50	6.14	2.05	1.74	3.79
1862*	2:24	6.74	2.25	2.00	4.25
1870	2:25	6.75	2.25	2.00	4.25
2055	3:05	7.40	2.47	2.30	4.77
2050*	3:06	7.40	2.47	2.30	4.77
2350	3:50	8.26	2.75	2.75	5.50
2520	4:25	8.90	2.96	3.04	6.00
70*	8:00	0.40	0.13	0	0

Initial length: 3.002 inches
Final length: 3.002 inches
*Temperatures measured with chromel/alumel thermocouple

Table iii-b

The Thermal Conductivity of Tungsten Sheet
Using the Comparative Rod Apparatus
With Armco Iron References

Mean Temperature of Specimen °F	Thermal Conductivity of Specimen K_s Btu/hr/ft²/°F/in.	ΔT through Specimen °F	Mean Temperature of Lower Reference °F	Thermal Conductivity of Lower Reference K_1 Btu/hr/ft²/°F/in.	ΔT through Lower Reference ΔT_1 °F	Mean Temperature of Upper Reference °F	Thermal Conductivity of Upper Reference K_2 Btu/hr/ft²/°F/in.	ΔT through Upper Reference ΔT_2 °F
Run 1 on Specimen 1, 4-19-66 Diatomaceous earth insulation								
53.6	1294	2.30	46.3	517	5.95	60.9	511	5.63
51.8	1268	2.71	43.3	516	6.69	60.3	510	6.71
69.1	1270	3.18	59.4	511	7.84	79.3	506	8.05
213	1161	4.57	200	470	10.5	228	462	12.3
233	1128	4.76	220	465	10.8	248	458	12.5
255	1128	4.42	242	459	10.9	268	451	11.0
363	1054	8.10	340	433	19.2	388	421	20.8
440	1037	10.2	411	417	24.9	471	401	26.9
Run 2 on Specimen 1, 4-22-66 Thermatomic carbon insulation								
528	1023	3.50	513	392	8.77	541	386	9.65
821	959	6.82	796	331	19.3	845	321	20.8
913	963	6.64	887	312	20.8	937	301	20.9
1239	896	6.51	1214	249	22.3	1264	241	25.4
1289	911	6.93	1264	240	25.7	1316	231	28.0
Run 3 on Specimen 1, 4-26-66 Thermatomic carbon insulation								
1023	853	9.15	997	290	27.2	1050	280	27.5
1416	751	10.5	1032	221	36.0	1450	211	37.0

Notes: 1. All measurements made in an helium atmosphere. Apparatus was evacuated several times and purged with helium during run.

2. Conductivity was measured in the direction parallel to the plane of the sheet. The sheet was about 0.060 inches thick.

3. Chromel - alumel thermocouples were used for temperature measurements.

4. Conductivity calculated from following equation:

$$K_s = \frac{K_1 \Delta T_1 + K_2 \Delta T_2}{2 \Delta T_s}$$

Table iv-b

The Thermal Conductivity of Tungsten Sheet
Using the Radial Inflow Apparatus

SRI Run Number	Time	Specimen Outer Face Temperature °F	ΔT Across $\frac{3}{8}$" Specimen Gage Length °F	Total Heat Removed by $\frac{1}{2}$" Calorimeter Gage Length Btu/hr	Mean Temperature of Specimen °F	Specimen Thermal Conductivity Btu/hr/ft^2/°F/in.
Run 1 on Specimen 1 Cal. A-5 4-27-66	On 10:30					
	12:30	2100	51*	1374	1819	765
		2100	51	1390	1816	774
		2100	51	1332	1816	742
		2100	51	1356	1821	755
	2:40	2620	71*	1899	2444	760
		2620	71	1738	2448	695
		2640	71	1727	2461	691
		2640	71	1744	2466	698
	4:00	3110	80*	1999	3045	710
		3110	80	1962	3045	697
		3200	80	1927	3135	684
		3200	80	1944	3135	690
Run 2 on Specimen 1 Cal. A-5 4-28-66	On 9:40	2320	51*	1366	2152	760
	11:00	2320	51	1362	2153	758
		2320	51	1384	2156	771
		2320	51	1352	2158	753
	1:00	3210	75*	1798	3150	681
		3210	75	1883	3150	713
		3210	75	1785	3150	676
		3210	75	1794	3150	679
	11:30	3260	75*	1837	3200	695
		3260	75	1825	3200	691
		3260	75	1814	3200	687

Notes: 1. All measurements were made in an helium atmosphere.
2. Conductivity was measured in direction parallel to the plane of the sheet. The sheet was about 0.060 inches thick.
3. Specimen temperature gradients (noted with asterisk*) were measured with either chromel / alumel thermocouples, platinum/platinum-10 rhodium thermocouples, or with an optical pyrometer; ΔT used represents an average of several measurements.

Table v-b

The Enthalpy of Tungsten Sheet

Apparatus and Specimen Number	SRI Run No.	Initial Weight Grams	Final Weight Grams	Final Cup Temperature °F	Change in Cup Temperature °F	Drop Temperature °F	Enthalpy from Drop Temperature to 32°F Btu/lb
Adiabatic Calorimeter	1	26.150	26.150	91.22	-1.30	-65.3	-4.12
	2	26.682	26.682	88.39	-1.30	-62.7	-4.10
	3	36.878	36.878	74.32	1.32	214	5.62
	4	36.862	36.862	75.87	1.37	208	5.81
	5	36.862	36.860	79.23	3.23	396	12.0
	6	36.860	36.858	82.65	3.33	417	12.5
	7	36.858	36.857	87.00	4.57	635	19.6
	8	30.652	30.652	92.43	5.91	800	25.1
	9	30.652	30.651	97.91	6.13	834	26.2
	10	30.651	30.651	84.74	7.51	981	31.1
	11	30.651	30.650	91.91	7.39	979	30.9
Ice Calorimeter	12	59.550	59.560	-	-	1314	37.4
	13	59.560	59.560	-	-	1295	37.6
	14	59.560	59.560	-	-	1605	44.2
	15	59.560	59.565	-	-	1605	50.4
	16	59.565	59.560	-	-	1920	63.2
	17	59.560	59.545	-	-	1940	61.9
	18	59.545	59.540	-	-	2220	75.2
	19	59.540	59.540	-	-	2205	74.1
	20	59.540	59.530	-	-	2540	81.9
	21	59.530	59.530	-	-	2525	85.5
	22	59.530	59.535	-	-	2820	95.7
	23	59.535	59.535	-	-	2830	97.9
	24	59.535	59.535	-	-	3115	115
	26	59.535	59.525	-	-	3140	110
	27	59.525	59.520	-	-	1605	45.9

Table vi-b

The Enthalpies and Heat Capacities of Sheet Tungsten and TZM
Calculated from the Equations Fitted to the Experimental Data
and From the Graphical Solutions

Temperature °F	Tungsten Sheet				TZM Sheet				Temperature °R
	Enthalpy Btu/lb		Heat Capacity Btu/lb/°F		Enthalpy Btu/lb		Heat Capacity Btu/lb/°F		
	Eq. 3	Graphical Solution	Eq. 4	Graphical Solution	Eq. 5	Graphical Solution	Eq. 6	Graphical Solution	
40	0.[illegible]	0	0.033	0.033	0.44	0	0.065	0.063	500
540	16.4	17	0.026	0.033	33.6	32	0.063	0.064	1000
1040	31.0	34	0.029	0.034	66.4	65	0.066	0.066	1500
1540	46.9	51	0.033	0.034	100	98	0.069	0.068	2000
2040	64.9	68	0.038	0.035	136	135	0.072	0.075	2500
2540	85.1	85	0.042	0.037	173	175	0.076	0.087	3000
3040	10[illegible]	106	0.047	0.047	-	-	-	-	3500

Notes: The equations are as follows: (T in degrees Rankine):

Tungsten

3. $h_{32} = 1.303 \times 10^{-2} T + 483 \times 10^{-8} T^2 - 5871\ T^{-1} + 4.449$
4. $HC = 1.303 \times 10^{-2} + 966 \times 10^{-8} T + 3784\ T^{-2}$

TZM

5. $h_{32} = 5.444 \times 10^{-2} T + 350 \times 10^{-8} T^2 - 3343\ T^{-1} - 20.96$
6. $HC = 5.444 \times 10^{-2} + 700 \times 10^{-8} T + 1762\ T^{-2}$

Table vii-b

The Thermal Expansion of TZM Sheet
Using the Quartz Tube Dilatometer

Temperature °F	Time	Observed Total Elongation 10^{-3} in.	Observed Unit Elongation 10^{-3} in. /in.	Unit Elongation Correction for Dilatometer Motion 10^{-3} in. /in.	Corrected Specimen Unit Elongation 10^{-3} in. /in.
Run 1 on Specimen 1					
77.5	9:48	0	0	0	0
150	10:15	0.52	0.17	0.02	0.19
298	10:57	1.70	0.57	0.07	0.64
450	11:42	2.95	0.98	0.12	1.10
598	12:40	4.05	1.35	0.16	1.51
150	1:03	0.50	0.17	0.02	0.19
81.5	2:15	0.02	0.01	0	0.01
Run 2 on Specimen 1					
81.5	2:20	0	0	0	0
150	3:03	0.50	0.17	0.02	0.19
302	3:33	1.65	0.55	0.07	0.62
450	4:30	2.88	0.96	0.12	1.08
605	5:46	4.10	1.37	0.16	1.53
748	6:36	5.34	1.78	0.19	1.97
81.5	8:00	0.02	0.01	0	0.01

Initial length: 2.999 inches
Final length: 2.999 inches
(Both Runs)

Table viii-b

The Thermal Expansion of TZM Sheet
Using the Graphite Dilatometer

Temperature °F	Time	Observed Total Elongation 10^{-3} in.	Observed Unit Elongation 10^{-3} in. /in.	Unit Elongation Correction for Dilatometer Motion 10^{-3} in. /in.	Corrected Specimen Unit Elongation 10^{-3} in. /in.
Run 3 on Specimen 1 (Dilatometer No. 4)					
70	10:35	0	0	0	0
853	12:15	4.8	1.60	0.80	2.40
1066	1:00	6.1	2.03	1.01	3.04
1296	1:35	7.6	2.53	1.26	3.81
1545	2:00	9.1	3.03	1.55	4.58
1555	2:01	9.1	3.03	1.55	4.58
1740	2:30	10.25	3.42	1.80	5.22
1875	3:10	10.99	3.66	1.95	5.61
2095	3:35	12.63	4.21	2.25	6.46
2350	4:05	14.03	4.68	2.60	7.28
2520	4:45	15.13	5.04	2.85	7.89
70	8:00	0.42	0.14	0	0.14
Initial length:	2.999 inches				
Final length:	2.999 inches				
Run 4 on Specimen 1 (Dilatometer No. 4)					
70	8:40	0	0	0	0
1279	11:05	7.98	2.66	1.25	3.91
1575	12:20	9.60	3.20	1.58	4.78
1585	12:21	9.60	3.20	1.59	4.79
1775	1:35	10.61	3.54	1.85	5.39
2100	2:00	12.78	4.26	2.26	6.52
2305	2:40	14.04	4.68	2.54	7.22
2520	3:40	15.34	5.11	2.83	7.94
1825	4:00	10.61	3.54	1.90	5.44
1260	4:25	7.21	2.40	1.24	3.64
70	8:00	0.30	0.10	0	0.10
Initial length:	2.999 inches				
Final length:	2.999 inches				

Table ix-b

The Thermal Conductivity of TZM Sheet
Using the Comparative Rod Apparatus
With Armco Iron References

Mean Temperature of Specimen °F	Thermal Conductivity of Specimen K_s Btu/hr/ft²/°F/in.	ΔT through Specimen °F	Mean Temperature of Lower Reference °F	Thermal Conductivity of Lower Reference K_1 Btu/hr/ft²/°F/in.	ΔT through Lower Reference ΔT_1 °F	Mean Temperature of Upper Reference °F	Thermal Conductivity of Upper Reference K_2 Btu/hr/ft²/°F/in.	ΔT through Upper Reference ΔT_2 °F
Run 1 on Specimen 1, 4-14-66 Thermatomic carbon insulation								
595	687	6.07	582	377	9.99	609	371	12.3
703	705	5.70	690	354	11.1	717	348	11.8
1104	660	8.98	1082	274	21.4	1126	266	22.5
1186	663	9.25	1163	259	24.4	1209	250	23.8
1491	673	11.0	1458	209	37.2	1522	201	35.0
Run 2 on Specimen 1, 4-19-66 Thermatomic carbon insulation								
380	737	5.03	367	428	8.10	392	421	9.37
356	752	5.37	343	433	8.09	369	428	10.7
900	717	8.39	879	314	17.9	922	305	21.0
801	715	9.79	779	335	17.0	827	326	25.5
1393	703	18.7	1339	229	55.0	1450	211	65.0
Run 1 on Specimen 2, 4-20-66 Diatomaceous earth insulation								
63.7	833	4.58	52.9	514	7.65	76.3	507	7.29
85.6	831	5.24	73.5	507	8.56	99.8	500	8.74
284	828	9.89	263	452	17.4	309	441	19.3
340	819	8.90	320	439	16.7	363	428	17.0
460	811	13.3	430	411	26.2	493	397	27.2
550	797	17.3	511	392	34.8	594	375	37.2
Run 2 on Specimen 2, 4-25-66 Sifted Zirconia insulation								
258	758	4.47	247	458	6.07	271	451	8.87
461	732	6.15	446	408	10.1	477	400	12.2
1147	652	11.0	1120	267	26.9	1173	256	28.0

Notes:
1. All measurements made in an helium atmosphere. Apparatus was evacuated several times and purged with helium during the run.
2. Conductivity was measured in the direction parallel to the plane of the sheet. The sheet was about 0.053 inches thick.
3. Chromel/alumel thermocouples were used for temperature measurements.
4. Conductivity was calculated from following equation:

$$K_s = \frac{K_1 \Delta T_1 + K_2 \Delta T_2}{2 \Delta T_s}$$

Table x-b

The Thermal Conductivity of TZM Sheet
Using the Radial Inflow Apparatus

SRI Run Number	Time	Specimen Outer Face Temperature °F	ΔT Across $\frac{3}{16}$" Specimen Gage Length °F	Total Heat Removed by $\frac{1}{2}$" Calorimeter Gage Length Btu/hr	Mean Temperature of Specimen °F	Specimen Thermal Conductivity Btu/hr/ft²/°F/in.
Run 1 on Specimen 1 Cal. A-5 4-22-66	On 10:30 12:40	2070	49	1273	1922	738
		2070	49	1273	1922	738
		2070	48	1262	1924	747
	2:00	2160	57	1330	2044	663
		2160	58	1338	2043	666
		2180	57	1333	2043	664
		2170	57	1324	2046	660
	4:00	2680	66	1590	2515	685
		2670	63	1561	2512	704
		2670	64	1621	2504	720
		2670	61	1580	2502	735
Run 2 on Specimen 1 Cal. A-5 4-25-66	On 9:30 10:45	2610	50*	1227	2490	697
		2610	50	1294	2490	735
		2610	50	1292	2490	734
		2610	50	1242	2490	706
	1:30	2030	37	817	1940	627
		2060	36	836	1940	660
		2060	37	828	1944	635
		2070	37	834	1936	640
		2070	36	824	1935	650

Notes:
1. All measurements were made in an helium atmosphere.
2. Conductivity was measured in the direction parallel to the plane of the sheet. The sheet was about 0.053 inches thick.
3. Specimen temperature gradients were measured with either chromel/alumel thermocouples, platinum/platinum - 10 rhodium thermocouples, or with an optical pyrometer; the ΔT's marked with an asterisk (*) represent an average of several measurements.

Table xi-b

The Enthalpy of TZM Sheet

Apparatus and Specimen Number	SRI Run No.	Initial Weight Grams	Final Weight Grams	Final Cup Temperature °F	Change in Cup Temperature °F	Drop Temperature °F	Enthalpy from Drop Temperature to 32°F Btu/lb
Adiabatic Calorimeter	1	21.086	21.085	81.69	-1.71	-55.3	-6.57
	2	21.085	21.085	80.09	-1.43	-49.5	-5.05
	3	21.085	21.084	81.09	1.13	198	9.69
	4	21.084	21.084	75.69	1.24	196	9.98
	5	21.084	21.084	79.13	3.48	404	23.0
	6	21.084	21.083	82.78	3.56	422	23.6
	7	15.689	15.689	86.30	5.22	719	43.6
	8	15.689	15.690	90.09	5.00	705	42.1
	9	15.690	15.695	85.91	7.35	954	59.9
	10	15.695	15.697	92.83	7.09	936	58.3
Ice Calorimeter	12	36.415	36.410	-	-	1430	86.8
	13	36.410	36.415	-	-	1735	114
	14	36.415	36.415	-	-	2025	139
	15	36.415	36.425	-	-	1253	78.0
	16	36.425	36.400	-	-	2350	158
	17	36.400	36.415	-	-	1100	65.8
	18	36.415	36.410	-	-	1418	95.9
	19	36.410	36.410	-	-	1725	106
	20	36.410	36.390	-	-	2040	131
	21	36.390	36.385	-	-	2300	148
	22	36.390	36.385	-	-	2600	184
	23	36.385	36.390	-	-	2620	179